The Effect of Bimodal Stimulation on Pitch Ranking and Speech Recognition in Children with Cochlear Implants

A thesis submitted in partial fulfilment of

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Contents

Appendices

List of Abbreviations

BKB-A	Bamford Kowhal Bench-Australian (Sentences)
BE	Better (hearing) Ear
BM	Basilar Membrane
BMS	Bimodal Stimulation
CF	Characteristic Frequency
SNHL	Cochlear Hearing Loss
CI	Cochlear Implant
CNC	Consonant-Nucleus-Consonant (Words)
dB	Decibel
dBHL	Decibels Hearing Level
dBSPL	Decibels Sound Pressure Level
DSL	Desired Sensation Level
EAS	Electro-acoustic Stimulation
ERB	Effective Rectangular Bandwidth
F0	Fundamental Frequency
HA	Hearing Aid
HINT	Hearing in Noise Test
IEEE	Institute of Electrical and Electronics Engineers
LQ	Lower Quartile
NAL-NL1	National Acoustic Laboratories (Australia) Non-linear 1
NH	Normal-Hearing
PMMA	Primary Measures of Musical Audiation
PPLDPQ	Parental Perceptions of Listening Device Performance Questionnaire
PRT	Pitch Ranking Task
QOL	Quality of Life
SCIC	Sydney Cochlear Implant Programme (Australia)
SCIP	Southern Cochlear Implant Programme (New Zealand)
SDR	Score Difference Residual
SGN	Spiral Ganglion Neuron
SNR	Signal-to-Noise Ratio
SSN	Steady-State Noise
TFS	Temporal Fine Structure
UoC	University of Canterbury
UQ	Upper Quartile

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Abstract

Data from normal-hearing (NH) listeners indicates that access to the low-frequency, low-numbered harmonics in complex sounds is important for the perceptual segregation of competing sounds (see Oxenham, 2008 for a review). Poor frequency selectivity is experienced by many listeners with sensorineural hearing loss, resulting in reduced perceptual access to individual harmonics (Arehart, 1994; Bernstein & Oxenham, 2006b; Moore, 1996). In addition, the commercially available speech processing strategies used in current cochlear implants (CIs) provide little or no representation of individual harmonics (see B. C. J. Moore, 2003 and; Wilson & Dorman, 2008 for a review).

Improvements in CI technology and concurrent improvements in speech perception outcomes have led to an expansion of the implantation criteria to include individuals with residual acoustic hearing in one or both ears. A growing body of evidence supports the use of bimodal stimulation (BMS) in such individuals (e.g. Beijen, Mylanus, Leeuw, & Snik, 2008; Ching, Incerti, & Hill, 2004; Ching, Incerti, Hill, & van Wanrooy, 2006; Dunn, Tyler, & Witt, 2005; Luntz, Shpak, & Weiss, 2005; Mok, Grayden, Dowell, & Lawrence, 2006). Bimodal stimulation involves the electrical stimulation of one ear via a CI, and acoustic stimulation of the contralateral ear via a hearing aid (HA). Evidence suggests that BMS may improve the speech recognition in noise performance of CI users, and allow for improved music perception through the provision of additional pitch cues (Ching, Psarros, Hill, Dillon, & Incerti, 2001; Kong & Carlyon, 2007; Kong, Stickney, & Zeng, 2004; McDermott, Sucher, & Simpson, 2009; Mok, Galvin, Dowell, & McKay, 2007; Sucher, 2007; Sucher & McDermott, 2007).

The present study compared the speech recognition and pitch ranking abilities of 16 NH children, 8 children using a unilateral CI (CI-only group); 6 children with a severe-profound hearing loss using bilateral HAs (HA-only group), and 9 children who were experienced users of BMS (eBM group). In addition, a single CI-only user (Case A) with residual

hearing in their non-implanted ear was fitted with a contralateral HA, and their performance was assessed using their CI-alone and after 3 months experience using BMS.

It was hypothesised that: (i) The eBM group would score higher than the CI-only group for tasks of word recognition in quiet; (ii) there would be no difference between the sentence recognition in quiet scores of the CI-only, HA-only and eBM groups; (iii) the eBM and HA-only groups will score higher than the CI-only group on tasks of sentence recognition in noise; (iv) the eBM group will rank pitch more accurately than the CI-only group, but not the HA-only group, and; (v) that the addition of an optimally fitted HA in the non-implanted ear of children using a CI will result in improved speech recognition in quiet and noise, and improved pitch ranking accuracy.

Participants were assessed using their normal listening devices using; the Consonant-Nucleus-Consonant (CNC) word lists in quiet; the Hearing In Noise sentence test (HINT) in quiet (S0) and in spatially coincident (S0N0) and spatially separated (S0NCI, S0NHA) 4-talker babble, using a 10 dB signal-to-babble ratio; and a pitch ranking task (PRT) using 1, ½ and ¼ octave interval sizes. All testing was conducted in a soundfield.

There were no significant differences between the mean scores of the CI-only, HA-only and eBM groups for either the CNC word lists in quiet, or the HINT sentences in quiet or noise, participants scoring at ceiling levels for all four HINT listening conditions. There was also no improvement in Case A's CNC word scores, however their HINT sentence scores improved by 23.7% points in quiet and by an average of 11.9% points in noise following the addition of a contralateral HA. These improvements were greater in size than the largest learning effect seen in the CI-only and HA-only groups for 3 of the 4 HINT listening conditions. For the PRT, there were no significant differences between the scores of the CI-only and eBM groups. As expected, the NH group scored significantly higher than the CI-only and eBM groups on all three subtests ($p < 0.05$). The HA-only group scored significantly higher than the CI-only and eBM groups on the 1 and ½ octave subtests. There were no significant differences between the scores of the NH group and HA-only groups on all three subtests. Case A's PRT scores were higher in the BMS (*M* = 83.3% correct) than the CI-only condition (*M* = 74.0%). This improvement was considerably greater than the largest learning effect seen in the CI-only and HA-only groups for the 1 and ½ octave subtests for stimuli with fundamental frequencies ≤ 262 Hz.

Overall, we found limited evidence in support of the hypothesis that the additional low-frequency pitch information provided via acoustic hearing in BMS allows for improved speech perception in quiet and noise, and improved pitch perception in prelingually deafened CI users. However, child CI users (CI-only and eBM groups) did rank pitch more accurately than adult CI-only users in previous studies. The higher plasticity of the central auditory nervous system of child CI users may have enabled more effective adaptation to electrical stimulation, allowing them to more effectively utilise available pitch cues than their adult counterparts. We recommend that future research isolate the contribution of the non-implanted ear to auditory perception in children using BMS, and investigate whether musical training is capable of enhancing pitch perception in users of a unilateral CI or BMS.

To listen to simulations illustrating the benefits of bimodal stimulation for music perception, created during this study, please visit '<u>thelisteningtree.wordpress.com</u>'

1 Introduction to Hearing and Hearing Loss

In order to better understand the differences between acoustic and electric hearing, an understanding of the fundamentals of hearing, hearing loss, hearing aids and cochlear implants is essential.

1.1 Normal Hearing

In normal hearing, sound passes along the ear canal and induces vibration of the eardrum. These vibrations are conducted via the ossicular chain (malleus, incus and stapes) to the oval window of the inner ear (see *Figure 1.1*). The inner ear, or cochlea, consists of triad of fluid-filled ducts (scala media, scala vestibuli and scala tympani) that spiral around a central bony hub known as the modiolus, which has a hollow centre containing the spiral ganglion (see *Figure 1.2*).

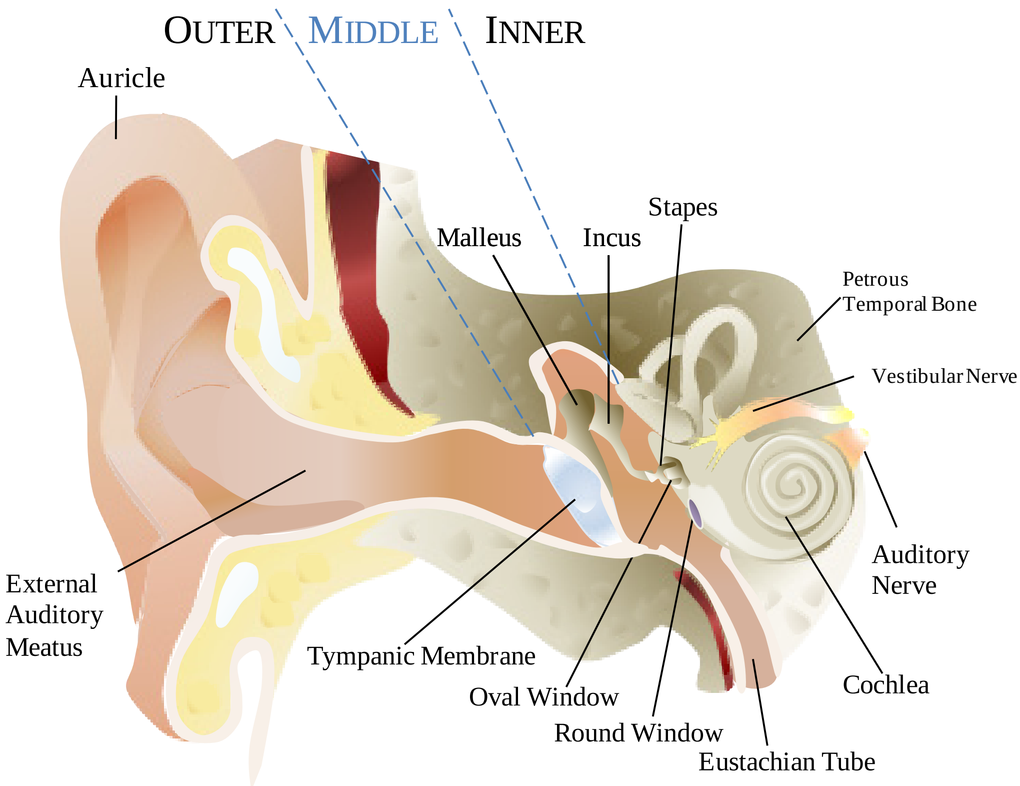

Figure 1.1: **Illustration of the gross anatomy of the peripheral auditory system.**
Re-drawn and adapted from Papsin & Gordon (2007)

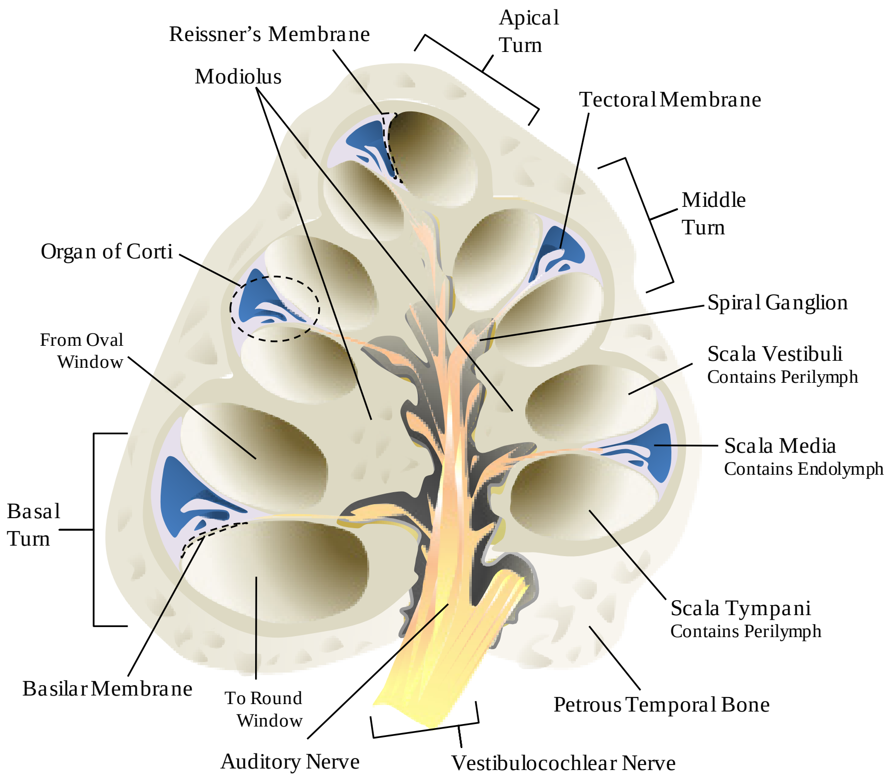

Figure 1.2: **An illustrated cross section of the cochlea.**
Re-drawn and adapted from Martini, Timmons & Tallitsch (2003).

Inside scala media is the organ of Corti, which is comprised of sensory hair cells and numerous supporting cells (see *Figure 1.3*). Sound-induced vibration at the oval window results in the transfer of pressure along the length of the cochlea and displacement of the basilar membrane (BM). This results in the movement of hair cell stereocilia, the release of neurotransmitter from stimulated hair cells and a change in the firing rate of spiral ganglion neurons (SGNs), perceived by the central auditory nervous system as sound.

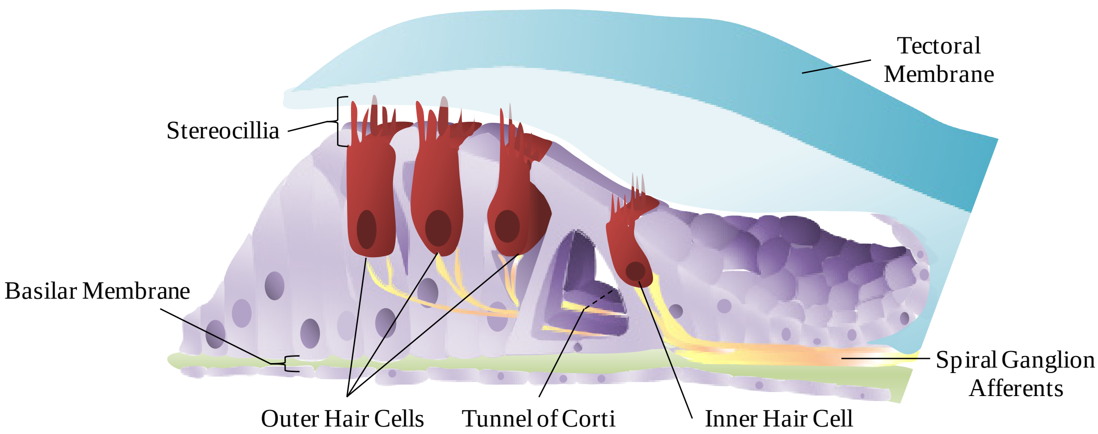

Figure 1.3: **A simplified cross section of the organ of Corti.**
Re-drawn and adapted from Martini et al. (2003).

1.2 Hearing Loss

There are three types of hearing loss: conductive, mixed, and sensorineural (SNHL). For the purposes of the present study, we will focus only on SNHL, in which damage to cochlear hair cells and/or SGNs results in the reduced audibility of sound, distortion, and impaired auditory discrimination. Clinically, the level of hearing loss is assessed using puretone audiometry (Carhart & Jerger, 1959) to obtain hearing thresholds (see *Figure 1.4*). The level of functional impairment resulting from a cochlear hearing loss is determined using speech recognition testing. An individual's suitability for and ability to benefit from HA(s) and/or a CI is determined using this information.

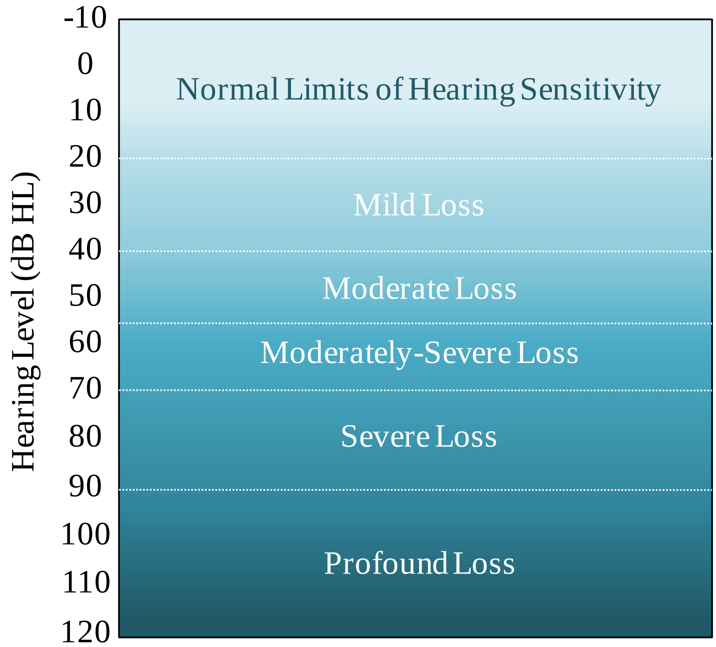

***Figure 1.4*: Classification of the levels of hearing impairment in New Zealand.**

1.3 Hearing Aids

Hearing aids are one option for managing SNHL and are designed to increase the audibility of sounds, while maintaining loudness comfort. The primary components of a basic digital hearing HA are illustrated in *Figure 1.5*. Sound is converted by a microphone into an electrical signal that is digitised and modified by a digital signal processor. The output signal is then amplified, and converted back into an acoustic signal that is ported to the ear canal. HAs in the present study used some form of compression to fit the wide range of sound levels in the acoustic environment into the reduced dynamic range of the individuals with SNHL. Compression is used to increase the audibility of soft and moderate level sounds and to limit the level of loud sounds, reducing distortion and improving comfort in noisy situations.

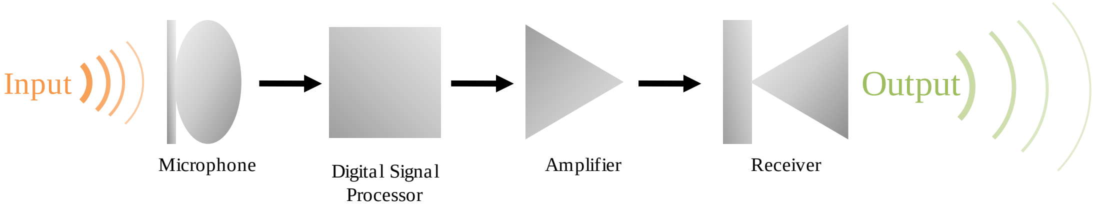

Figure 1.5: **Block diagram of the basic components of a hearing aid**

HAs are fitted to individuals using a prescriptive formula which calculate targets for the gain, compression and maximum power output of the aid. In the present study either the National Acoustics Laboratories non-linear (NAL-NL1) or the Desired Sensation Level ($DSL_{[I/O]}$) fitting formula were used. With an emphasis on habilitative audibility, $DSL_{[I/O]}$ tends to prescribe the maximum comfortable amplification at each frequency (Seewald, Moodie, Scollie, & Bagatto, 2005). NAL-NL1 focuses on speech intelligibility, and tends to prescribe less low-frequency amplification to reduce upward the spread of masking (Dillon, 1999). NAL-NL1 may not prescribe targets for certain frequencies where amplification of sound is likely to result in reduced speech intelligibility (Dillon, 1999).

1.4 Cochlear Implants

In some individuals with a severe-to-profound hearing loss, the extent and pattern of cochlear pathology may preclude the adequate perception of acoustic cues essential for speech recognition, even with properly optimised HAs. Such individuals may obtain better speech recognition through a CI, which uses direct electrical stimulation to bypass damaged or missing hair cells and activate spiral ganglion neurons (SGNs), re-instating afferent input to the central auditory nervous system.

Participants in the present study used the Nucleus CI24 implant system, the components of which are illustrated in Figure *1.6* and Figure *1.7*, and include: (1) a microphone that converts sound into a digital signal; (2) a speech processor that uses a pre-programmed MAP and speech processing strategy to transform the input signal into a pattern of electrical pulses to be sent to the implanted electrodes; (3) a radiofrequency coil for the transmission of power and stimulus information across the skin; (4) a receiver-stimulator package implanted within the mastoid bone, which decodes the stimulation information and sends it to; (5) an intracochlear electrode array, inserted into scala tympani.

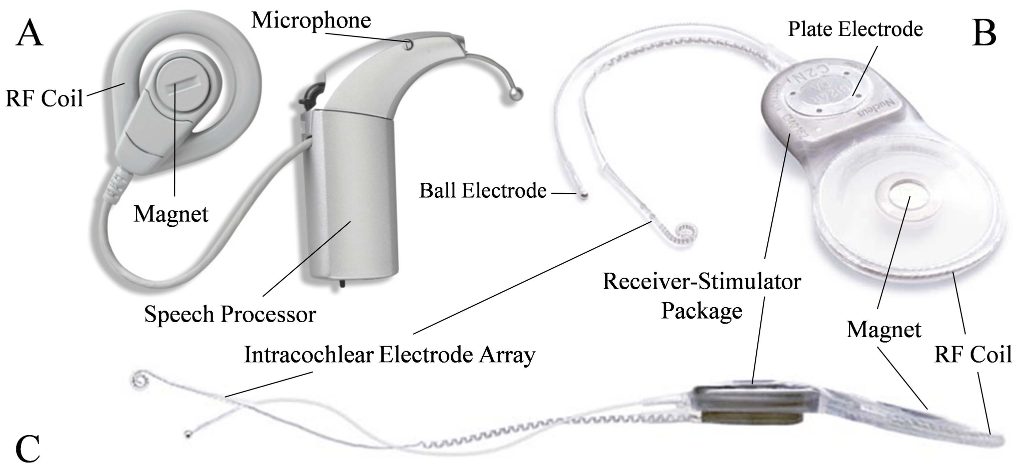

Figure 1.6: **Components of a Cochlear Implant system.**

Nucleus CI24 and ESPrit 3G processor pictured. A: External components. B: Internal components, top down view. C: Internal components, horizontal view ("Cochlear Product Photos," 2008).

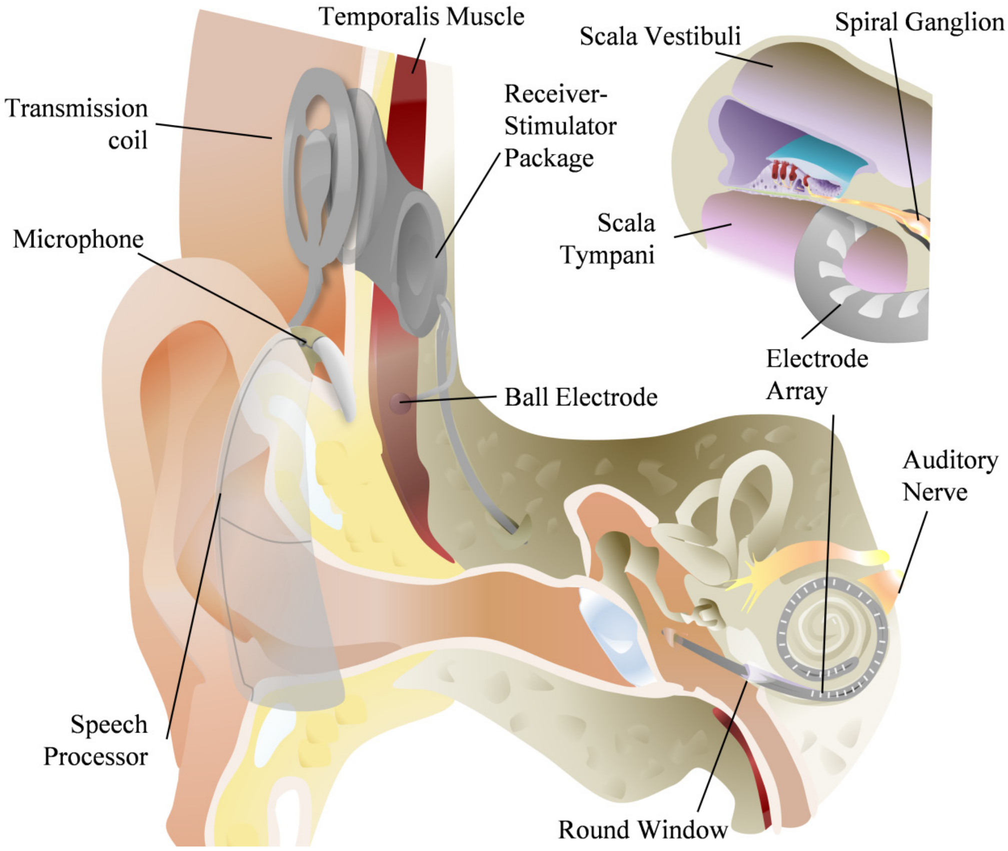

Figure 1.7: **Cross section illustrating the placement of the components of a cochlear implant system.** Re-drawn and adapted from Papsin and Gordon (2007).

CI candidacy is based upon an individual's aided and unaided hearing thresholds, and aided speech recognition scores. The candidacy criteria for participants in the present study included; (1) the potential to benefit more from a CI than properly fitted and optimised HAs; (2) a bilateral severe to profound SNHL at 2 kHz and above with aided and unaided hearing thresholds equal to, or worse than the levels indicated in *Figure 1.8*; (3) a lack of auditory progress with HAs, and; (4) aided speech recognition scores as indicated below:

- For the Sydney Cochlear Implant Centre (SCIC): Open-set Bamford-Kowal-Bench (BKB-A) sentence recognition scores, and Consonant-Vowel-Consonant phoneme scores of ≤ 40% correct in the ear being considered for implantation;
- For the Southern Cochlear Implant Programme (SCIP) of New Zealand: Hearing in Noise Test (HINT) sentence recognition in quiet scores of ≤ 50% correct for the ear to be implanted and ≤ 60% correct for the contralateral ear, or ≤ 60% correct when sentences are presented binaurally.

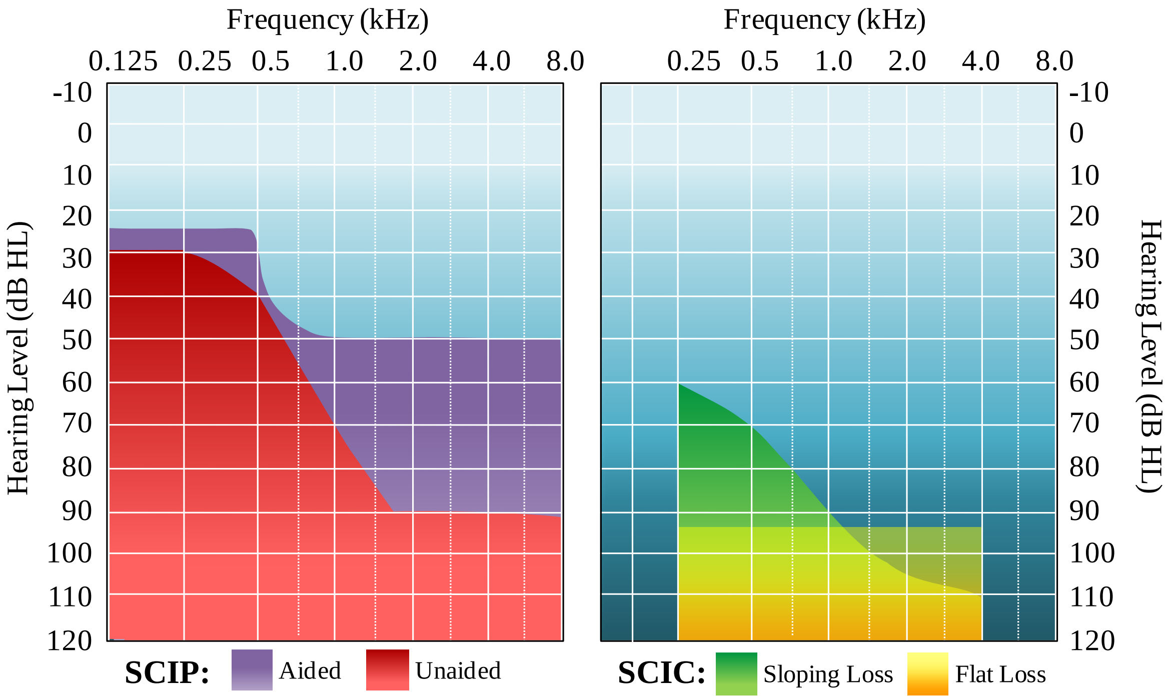

Figure 1.8: **Hearing threshold referral criteria for CI assessment.**

1.5 Bimodal Stimulation

Originally proposed by Dooley et al. (1993), bimodal stimulation (BMS) combines electrical stimulation from a CI, with the acoustic stimulation of residual hearing via a contralateral HA. Electro-acoustic stimulation (EAS) (von Ilberg et al., 1999), is similar to BMS except that the acoustic and electric signals are presented to the same ear. While BMS always provides binaural input to the central auditory nervous system, EAS may be monaural or binaural (CI and binaural HAs). The acoustic residual hearing in BMS and EAS is thought to provide more reliable low-frequency pitch information than a CI-alone, potentially allowing for improved speech recognition in quiet, segregation of speech from competing noise, and improvements in sound quality, particularly in regards to music perception.

The Nucleus Hybrid L24 device (see *Figure 1.9*) is one device which uses electric stimulation to provide high-frequency information, and the acoustic amplification of low-frequency information to provide pitch information across the entire speech frequency range (Gantz & Turner, 2003, 2004). The unaided threshold and speech recognition criteria for Hybrid L24 candidates are outlined in *Figure 1.10*. Similar criteria have not yet been specifically established for BMS, however the guidelines of von Ilberg et al. (1999) may serve as a useful starting point (see *Figure 1.10*).

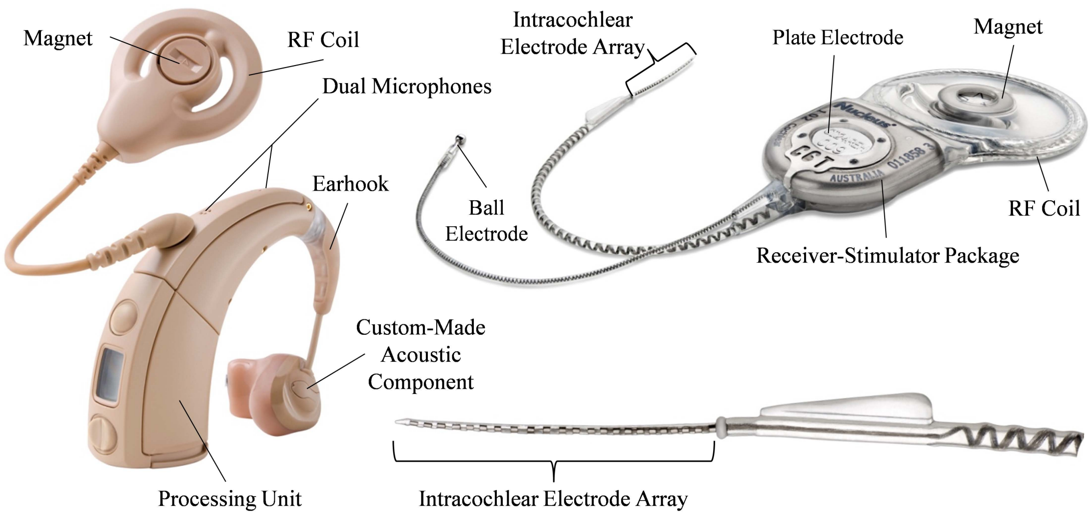

Figure 1.9: **Components of the Nucleus Hybrid L24 Implant System**

The Hybrid L24 electrode array has an insertion depth of only 10mm (25 - 28mm for standard arrays). Courtesy of Cochlear Europe Limited ("Library: Product Images," 2009).

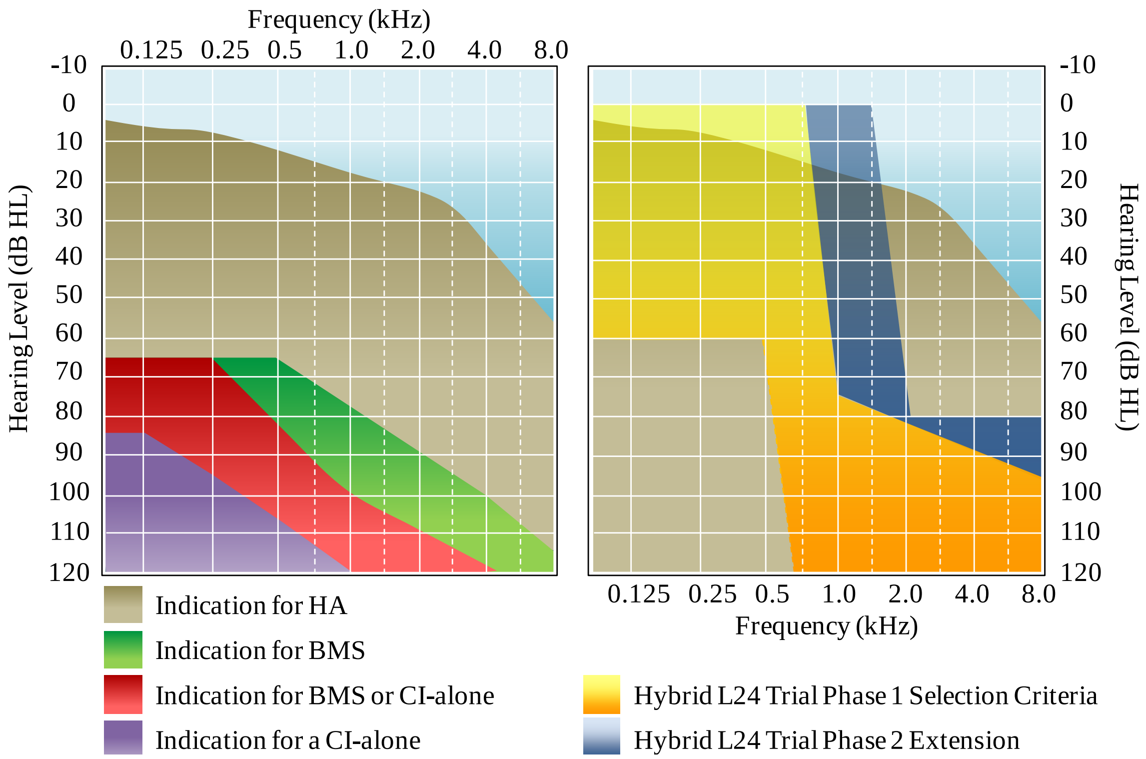

***Figure 1.10*:** **Unaided hearing thresholds for electro-acoustic stimulation candidates.**

Unaided threshold criteria for EAS proposed by von Ilberg et al. (1999), and for candidacy in the Hybrid L24 clinical trial, which also required CNC word recognition scores of 10% - 60% correct in the ear to be implanted and ≤ 80% correct in the contralateral ear (Gantz & Turner, 2003; Gantz, Turner, & Gfeller, 2006).

2 Pitch Coding

Although the fundamental principles of pitch coding in electric hearing are founded upon theories of pitch coding in acoustic hearing, the delivery of pitch information via a CI is limited by numerous physiological and technological constraints. The following is a discussion of pitch coding in acoustic and electric hearing, and a review of research into pitch perception outcomes in NH children, CI users and users of BMS.

2.1 Acoustic Hearing

2.1.1 The Coding of Sine Waves

Three theories are proposed to explain the coding of the pitch of a puretone: spectral-place, temporal, and spectro-temporal theories. In spectral-place theory, the frequency of a puretone is determined by the place of maximum vibration along the BM (see Figure 2.1). Each point along the BM responds best to a characteristic frequency (CF) that is related to the BMs mechanical characteristics. BM width and flexibility increase from the cochlear base to the apex, establishing a gradient of resonant frequencies. As a result the apical region of the BM vibrates best in response to low-frequency sounds, and the basal region of the BM vibrates best in response to high-frequency sounds, hence the BM has a tonotopic organisation. The CFs of hair cells and the SGNs that innervate them follow this tonotopic organisation.

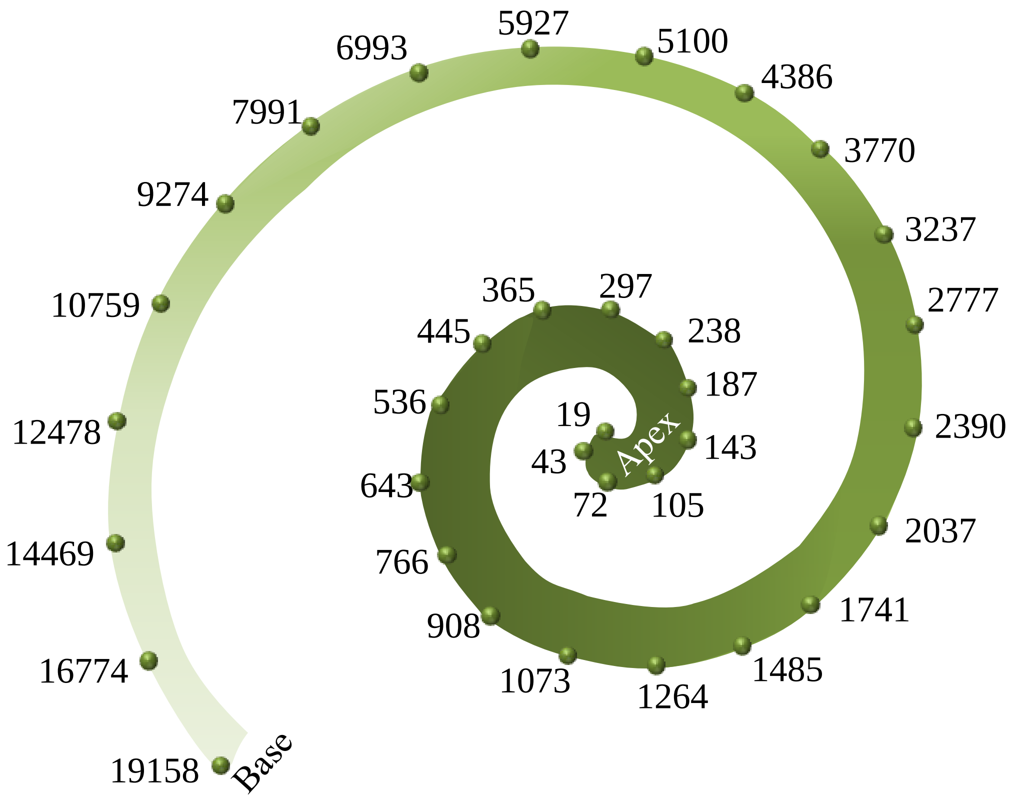

Figure 2.1: **The tonotopic organisation of the basilar membrane.**
The position of maximum displacement to sinusoids of differing frequencies (in Hz) is indicated. Redrawn and adapted from Loizou (1998).

Temporal theories propose that pitch is represented via neural firing synchrony within the auditory nerve. For frequencies below approximately 4 kHz auditory nerve spikes are more likely to occur at one phase of a sinusoid (puretone) than another, a phenomenon known as phase-locking (see panel A, *Figure 2.2*). The inter-spike intervals fall close to integer multiples of the period of the sinusoid, providing a potential code for stimulus frequency. However, individual SGNs fibers can only fire at a maximum rate of up to 800 Hz (Pickles, 1988). At frequencies above 800 Hz fibers may fire on every second, third or fourth cycle of the stimulus waveform. By pooling timing information across multiple SGNs that fire at alternate phases of the stimulus waveform, inter-spike intervals can be used to derive information about the frequency of the stimulus waveform (see panel B, *Figure 2.2*). This pooling of information is known as ‘the volley principle’ (Musiek & Baran, 2007).

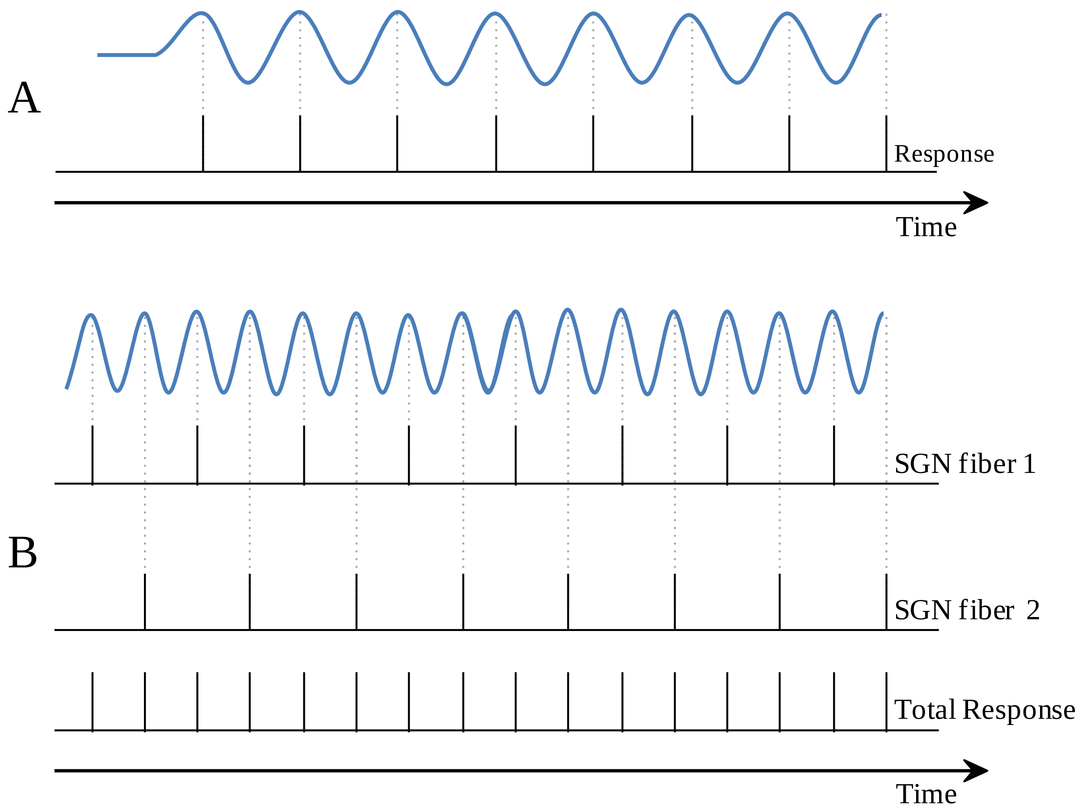

Figure 2.2: **Phase locking in spiral ganglion neurons.**
The above diagram illustrates the neural firing patterns of SGNs in response to; (A) a low frequency sinusoid, where the auditory fiber locks onto every cycle of the stimulus waveform and; (B) a high frequency sinusoid , where a the summation of responses from two SGN fibers (the total response) captures the temporal variation of the sine wave. Re-drawn and adapted from Musiek & Baran (2007).

Spectro-temporal theories combine both place and timing information. Different places on the BM vibrate with different phases, for example, when one point is moving upward, a nearby point may be moving downward, as seen in *Figure 2.3*. The rate of change in phase is particularly rapid near the point of maximum oscillation where nearby points can have a phase shift of 180° or more between them. The points along the BM that are in or out of phase with each other depend upon the frequency of the stimulating sound, thus a pattern of phase differences along the BM could be used by the auditory system to derive the frequency of a puretone (Loeb, White, & Merzenich, 1983).

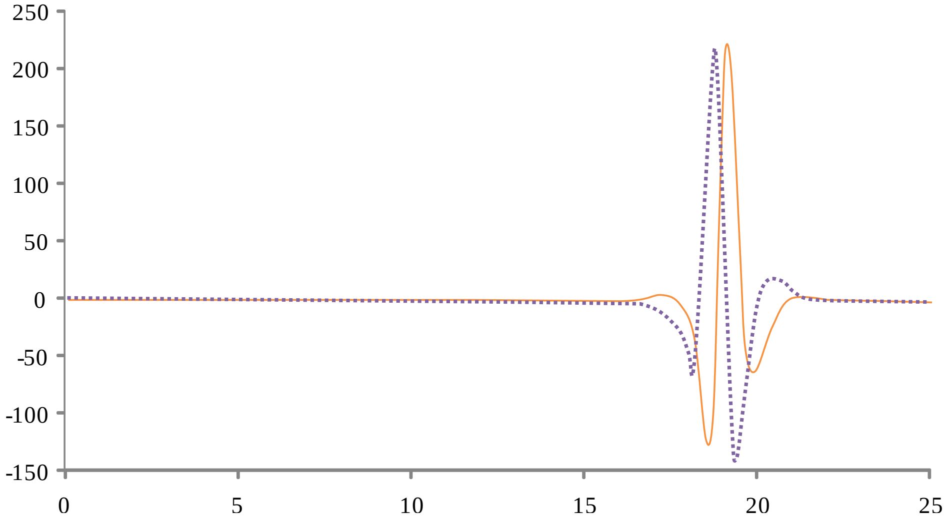

Figure 2.3: **Schematic of a travelling wave along the basilar membrane.** Snapshots are shown of the same travelling wave at two points in time, spaced one fourth of a cycle apart. Re-drawn from Oxenham (2008).

2.1.2 The Coding of Complex Sounds

Voiced speech and musical instruments are examples of complex harmonic sounds. These are usually comprised of a fundamental frequency (F0) and a series of harmonics with frequencies that are integer multiples of F0 (see *Figure 2.4*). Typically the pitch of a complex harmonic sound is determined by the F0.

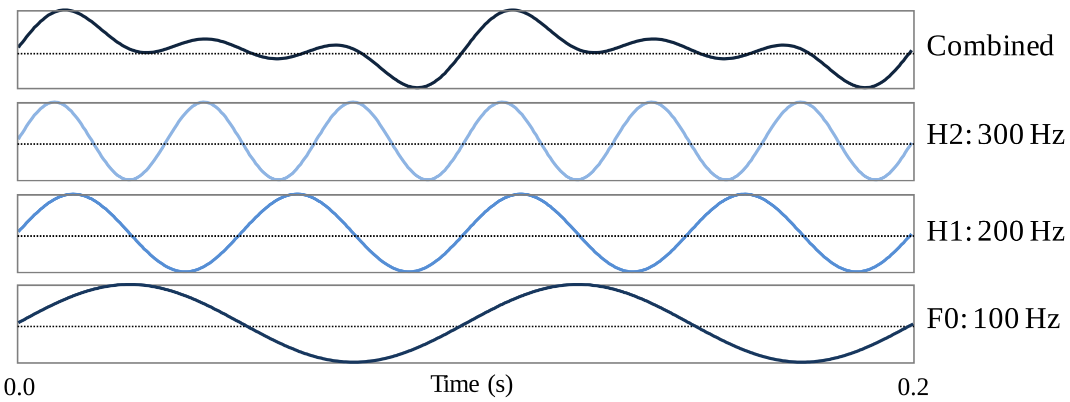

Figure 2.4: **Simplified illustration of the components of a synthesised complex harmonic tone** This complex tone is comprised of a sine wave with a fundamental frequency (F0) and two harmonics (H1 and H2).

Common to proposed models for the coding of the pitch of complex sounds is a focus on how the auditory system extracts information regarding the F0, and the initial spectral analysis conducted by the cochlea. Each point along the BM responds best to a CF, but will also respond to a small frequency range either side of this. In accordance with this the BM is often represented as an array of bandpass filters which analyse the input signal and divide it into its constituent frequency components (panel B1 *Figure 2.5*). Auditory filter bandwidths widen with increasing CF. Panel C (*Figure 2.5*) shows the resulting time-averaged filter output, or excitation pattern, of each filter. Because auditory filter bandwidths are smaller for low frequencies, low order-harmonics are more likely to fall within the bandwidth of a single auditory filter and form a distinct peak in the excitation pattern (i.e. they are resolved). At higher frequencies the bandwidth of auditory filters begins to exceed the spacing between adjacent harmonics. Thus, for two closely-spaced harmonics, not only will filters with the CF of these harmonics respond, but so too will filters with CFs between these harmonics. Sometimes a filter with a CF between two adjacent harmonics may even respond as strongly as filters with CFs the same as the harmonics. Peaks in the resulting excitation pattern become less distinct with increasing centre frequency, eventually disappearing, resulting in unresolved harmonics (panel C, *Figure 2.5*). Various models of pitch perception are based on this excitation pattern concept, in which resolved peaks in the excitation pattern are used to calculate the underlying F0 via preformed "harmonic templates." Low-order resolved harmonics have been shown to produce a stronger, more accurate pitch percept than higher-order unresolved harmonics (Bernstein & Oxenham, 2003; Houtsma & Smurzynski, 1990; Shackleton & Carlyon, 1994).

F0 information can also be extracted from the temporal waveform outputs of auditory filters for both resolved and unresolved harmonics (panel D, *Figure 2.5*). Low-order harmonics resolved by filters that are centred at or near the CF of one of the harmonic frequencies primarily respond to that single harmonic, producing a temporal waveform that 'beats' at a rate that is an integer multiple of the F0. Higher-order unresolved harmonics interact within each auditory filter producing a complex waveform with a temporal structure that repeats itself at a rate corresponding to the F0 (leftmost waveform, *Figure 2.5* panel D). It is thought that timing information can be pooled across all channels to derive the dominant periodicity,

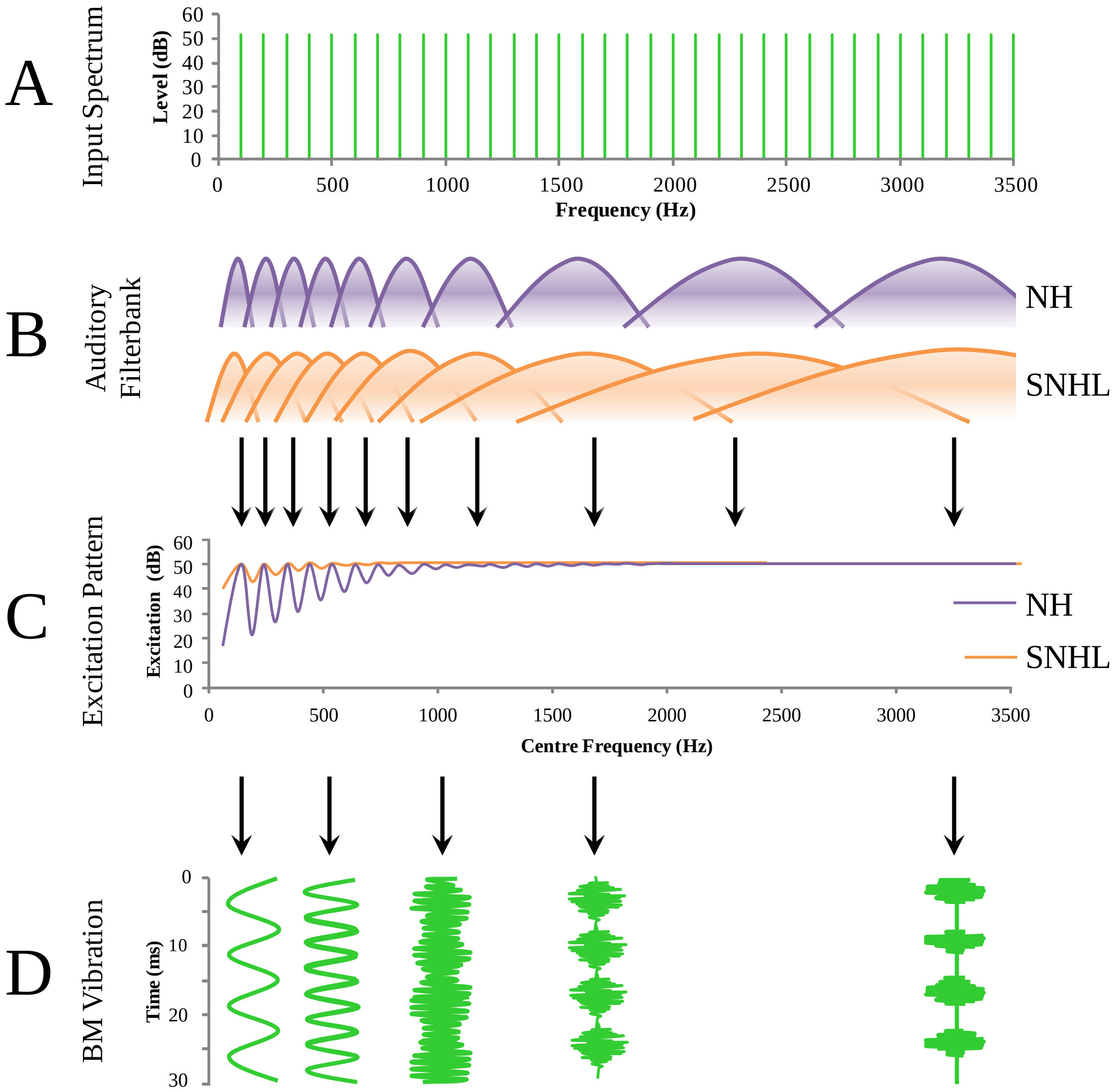

Figure 2.5: **Peripheral representation of a complex harmonic tone for NH and SNHL.**

Panel A is the power spectrum of a harmonic complex tone with a fundamental frequency of 100 Hz, and harmonics at multiples of this (i.e. 200, 300, 400, 500 Hz etc).

Panel B illustrates the characteristics of auditory filters which have wider absolute bandwidths as centre frequency increases. Two cases are represented; a normally functioning cochlea (NH, purple); and a flat, 60 dBHL SNHL aided to match HA prescription targets (orange). Note the substantially widened auditory filter bandwidths with a SNHL.

Panel C shows the time-averaged output of these filters as a function of the filter centre frequency; this is known as the excitation pattern. Note that the SNHL excitation pattern is less well defined despite suitable amplification.

Panel D shows the waveforms at the outputs of some sample auditory filters for NH only. Some lower filters only respond to one harmonic in a complex sound resulting in a sinusoidal output. Higher-frequency filters respond to multiple components producing a complex output with a temporal envelope that repeats at the rate of the F0.

Re-drawn and adapted from Plack & Oxenham (2005).

corresponding to the F0 (Cariani & Delgutte, 1996; Meddis & O'Mard, 1997). However, the phase relationships between the various components of unresolved harmonics are easily distorted in complex or reverberant environments, potentially limiting their usefulness (Bernstein & Oxenham, 2006a; Houtsma & Smurzynski, 1990; Shackleton & Carlyon, 1994).

The relative importance of spectral place and temporal pitch coding for complex sounds is still a matter of great debate, each code contributing to the salience of the other (see Oxenham, 2008 for a review). It may be that in NH, place and temporal pitch information are complementary, providing a highly redundant and robust pitch code in challenging listening environments (Oxenham, 2008).

2.1.3 Sensorineural Hearing Loss

In brief, widespread outer hair cell damage has been shown to impair pitch coding through the impaired ability to resolve low-order harmonics. Outer hair cells amplify low and moderate level sounds near their CF via an active process that acts to sharpen local BM responses. Outer hair cell damage results in a broadening of the BM response, the progressive widening of auditory filters, and a 'flatter' excitation pattern (*Figure 2.5*, panel B). This impairs the ability of the cochlea to resolve low-order harmonics, pitch perception becoming more reliant on temporal pitch cues (Arehart, 1994; Bernstein & Oxenham, 2006b; B. C. J. Moore & Peters, 1992). For an in-depth review of the effects of SNHL on sound perception see Moore (1996).

2.2 Developmental Maturation of Pitch Perception

Generation of a functional human cochlea is achieved by 30 weeks gestation, coinciding with the assembly of primary auditory circuits which have a precise tonotopic organisation (Illing, 2004; Kandler, Clause, & Noh, 2009; Pujol, Lavigne-Resbillard, & Uziel, 1991). Much of this development is genetically pre-programmed, however the fine-tuning of tonotopic maps in brainstem nuclei appears to require postnatal exposure to patterned auditory input from the environment (see Kandler et al., 2009 for a review). At the cortical level, exposure to patterned auditory stimuli is mandatory if tonotopic maps are to be established (see Eggermont, 2008, and; Illing, 2004 for a review). The results of neural imaging studies indicate that tonotopic maps of the right primary auditory cortex (Heschl's gyrus) are more finely tuned than those of the contralateral side (Leigeois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001; Zatorre, 2001) and may support fine-resolution pitch ranking judgments (Johnsrude, Pehune, & Zatorre, 2000).

Pitch discrimination and pitch ranking skills begin to develop in infancy, but do not fully mature until around 8 years of age (Duell & Anderson, 1967; Maxon & Hochberg, 1982; Stalinski, Schellenberg, & Trehub, 2008; Thompson, Cranford, & Hoyer, 1999). In general, the task of pitch discrimination is considerably easier than pitch ranking: determining a change in pitch direction (Cooper, 1994; Johnsrude et al., 2000). Pitch ranking is particularly difficult for children younger than 6 years of age, as they lack the concept of comparative relation and are unable to grasp the meaning of terms such as “higher” and “lower” in relation to pitch (Andrews & Madeira, 1977). Such difficulties are partly due to the multiple meanings of the terms “high” and “low” in the English language (Costa-Giomi & Descombes, 1996).

Stalinski, Schellenberg and Trehub (2008) compared the pitch ranking abilities of groups of NH children aged 5- (n = 26), 6- (n = 29), 8- (n = 30), and 11-years-old (n = 30), and young adults (n = 29). Stimuli were a set of 11 synthesised piano notes including one reference tone (F0 = 880 Hz) and five higher and five lower tones displaced in pitch by 4, 2, 1, 0.5 and 0.3 semitones upward and downward from the reference. Notes were presented in sequences of three, the second note being higher or lower in pitch than the first and third notes which were reference tones. Children were required to state whether the pitch of the second note was higher or lower than the pitch of the reference. Five and six-year-olds were able to accurately rank the pitch of two notes at a semitone interval size (see *Figure 2.6*), however, they were also less able to generalise training on the task across different interval sizes. It is possible that the poorer ability of younger children to discriminate pitch differences may have added to their cognitive load, exacerbating their difficulties on this pitch ranking task. Such difficulties were not present with eight-year-olds, whose performance was equivalent to that of untrained NH adults (see *Figure 2.6*).

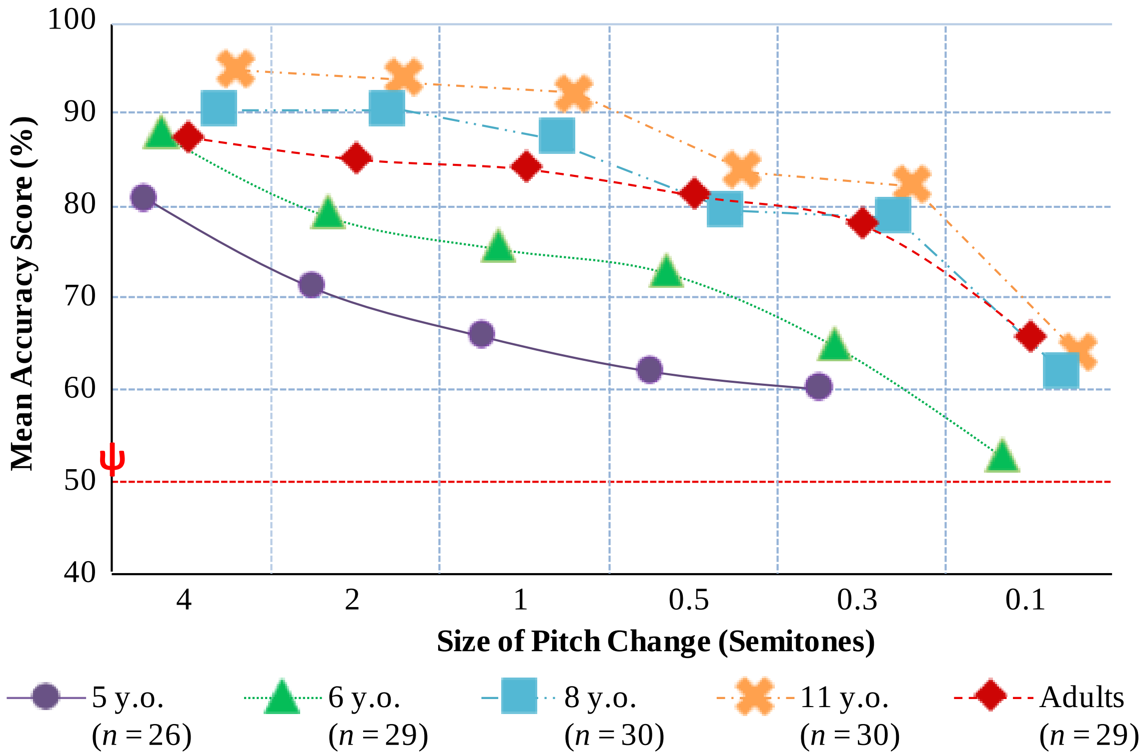

***Figure 2.6*:** **Comparison of the pitch ranking accuracy of normal-hearing children and adults.** ψIndicates level of chance performance. Adapted from Stalinski et al.(2008).

2.3 The Coding of Pitch in Electric Hearing

The coding of sound by a cochlear implant must be interpreted in the context of the capabilities of the speech processor, speech processing strategy, and an individual's customised MAP.

2.3.1 The Speech Processor and Speech Processing Strategies

Participants in the present study used either an ESPrit 3G or a Freedom processor. Some of the main differences between the two devices are summarised in Table 2.1. The Freedom speech processor also has Adaptive Dynamic Range Optimisation (ADRO) which enhances the audibility of soft and medium level sounds while maintaining overall loudness comfort, improved word recognition in quiet (James et al., 2002).

Processor	Microphone	Instantaneous Input Dynamic Range$^{\Phi}$	Frequencies Encoded
ESPrit 3G	Omnidirectional	30 dB	125 - 8,650 Hz
Freedom	Fixed Directional*	40 dB	190 - 7,940 Hz

Table 2.1: Differences between the ESPrit 3G and Freedom speech processors.

*A separate omnidirectional microphone is also available, however all users utilised the fixed directional microphone only. $^{\Phi}$Elaborated upon in section 7.1.1.

Each processor is programmed using a speech processing strategy that transforms the acoustic signal into a pattern of electrical stimulation. Participants in the present study used either the Spectral Peak (SPEAK) strategy or the Advanced Combination Encoder (ACE) strategies, the main features of which are illustrated in *Figure 2.7*.

In both strategies the acoustic input signal from the microphone is first passed through pre-emphasis filters to reduce the intensity of vowel sounds relative to weaker consonant sounds (Nogueira, Büchner, Lenarz, & Elder, 2005), and an automatic gain control which compresses loud sounds into the dynamic range of the listener (Wilson, 2006). The signal is then digitised and passes into a filterbank comprised of *m* bandpass filters (see *Figure 2.7*). The boundary frequencies of adjacent bandpass filters overlap slightly (Wilson, 2004). Filters are spaced linearly below 1 kHz, and logarithmically spaced above this, broadly mimicking the tonotopic organisation of the cochlea (Nogueira et al., 2005).

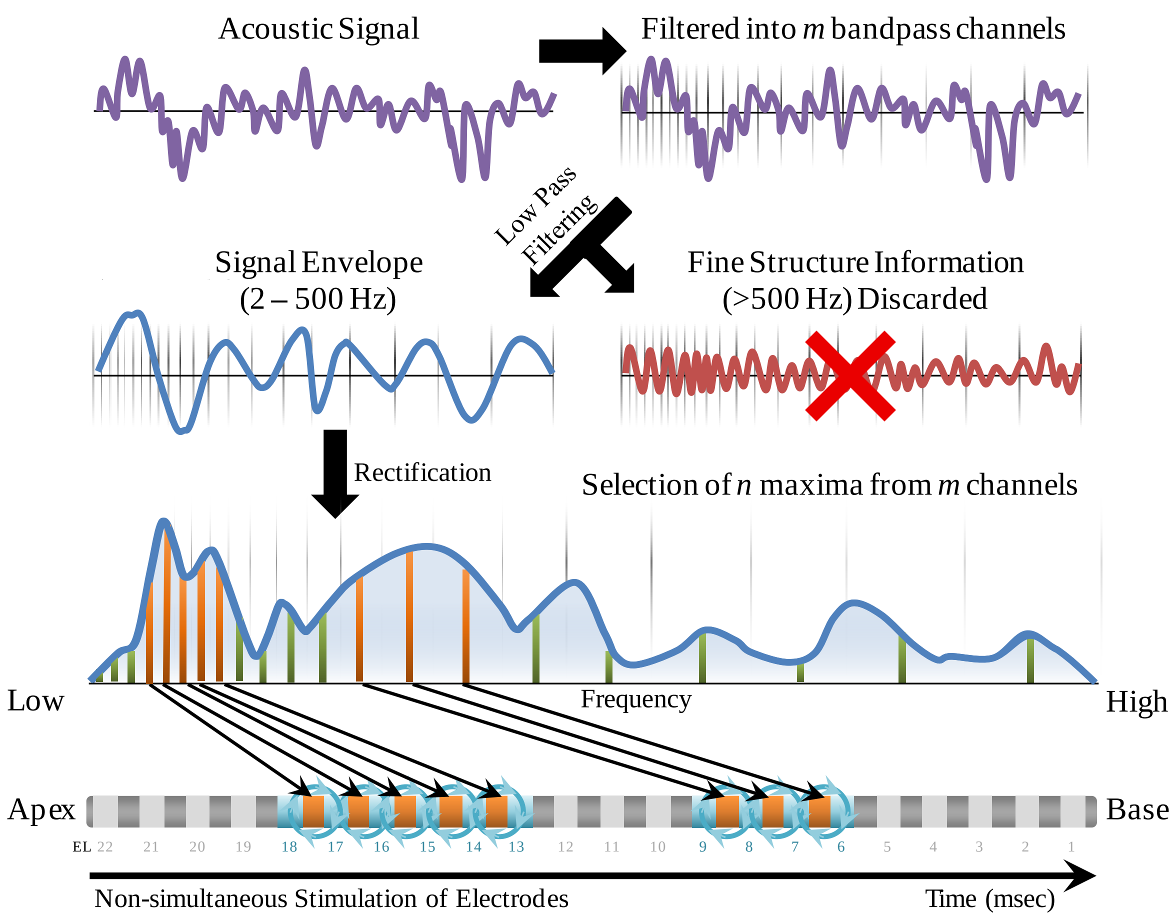

Figure 2.7: **Illustration of the features of an *n* of *m* strategy upon which the SPEAK and ACE strategies are based.**

1 cycle of stimulation is pictured. 'EL' is the electrode number.
m is limited to a maximum of 20 and 22 for the SPEAK and ACE strategies respectively.
Modified from Wilson (2006).

The signal envelope (2 – 50Hz), along with some information related to the periodicity (50 – 500 Hz) of the signal, is then extracted by low-pass filtering and rectification (see *Figure 2.7*). The signal envelope contains slow variations in the modulation of a signal which correspond with changes in the shape of the vocal tract for speech sounds (Wilson, 2004). The cutoff frequency of the low pass filter used is typically in the range of 200 – 400 Hz (Loizou, 1998), allowing for the encoding of periodicity-based cues relating to the F0 of voiced sounds (Wilson, 2004). Rapid variations in the modulated signal above 500 Hz, known as the temporal fine structure (TFS), are not included in the output signal for the SPEAK or ACE strategies. Removal of this information does not impair speech recognition in quiet, (Smith, Delgutte, & Oxenham, 2002) but does limit performance in other areas, as discussed in section 2.3.3.

For each stimulation frame, the short-term amplitude of the envelope output of each bandpass channel is sampled, with a subset of *n* channels with the highest short-term derived envelope amplitudes (spectral maxima) being selected (see *Figure 2.7*) (Nogueira et al., 2005; Wilson, 2004). The number of spectral maxima selected is specified in an individuals' MAP and can be: between 6 and 9 for the SPEAK strategy (Loizou, 1998) and; between 6 and 20 for the for the ACE strategy.

This subset of *n* channel outputs is then passed onto the "mapping" block which uses a logarithmic function to compress the envelope magnitude (Nogueira et al., 2005). The compressed envelope amplitude information from the subset of *n* channel outputs is used to modulate the amplitude of a train of fixed-rate balanced biphasic pulses as illustrated in *Figure 2.8*. The rate of stimulation for the SPEAK strategy is fixed at a maximum of 250 pulses per second (pps), however it can be set as high as high as 2400 pps for the ACE strategy (default is 900 pps) (Vandali, Whitford, Plant, & Clark, 2000).

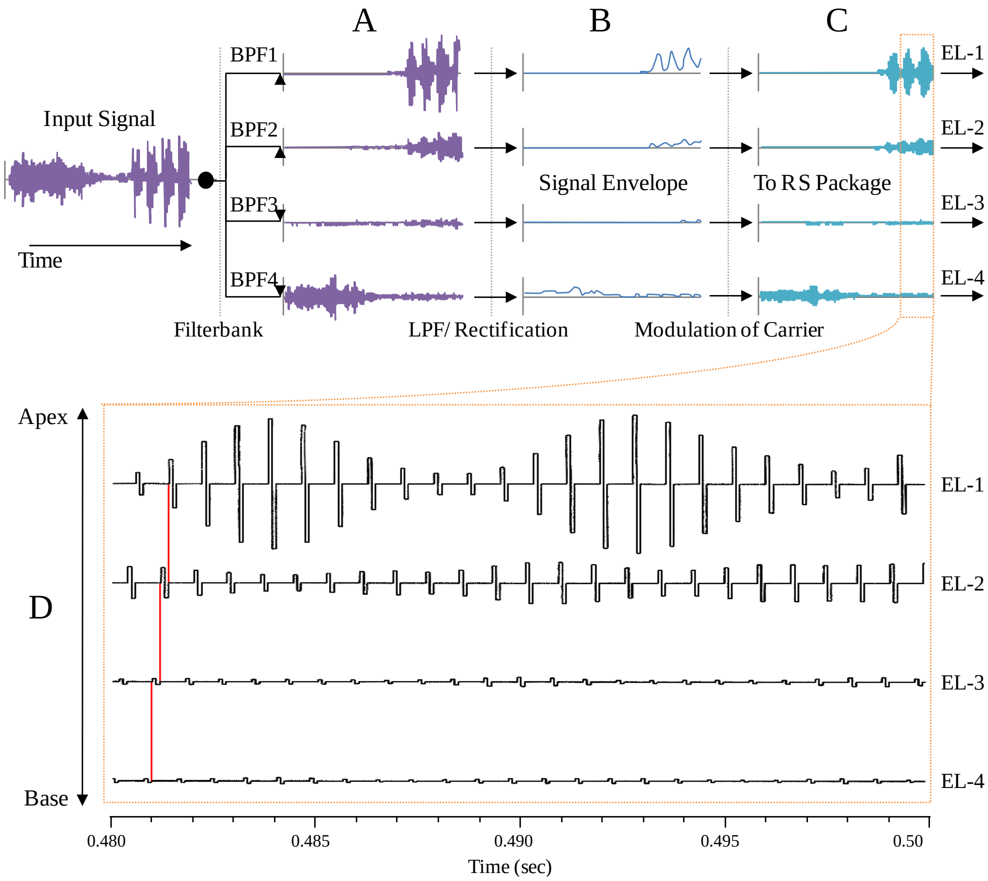

Figure 2.8: **Processing involved in a 4-channel Continuous Interleaved Sampling (CIS) strategy.** The CIS strategy is similar to the ACE and SPEAK strategies in terms of the order and types of processing, except that there is no selection and sampling of outputs. The above diagram illustrates the processing of input waveform of fixed-duration. The signal is split into several bandpass channels (A) and the envelope is extracted (B) and used to modulate a carrier signal (C). This is sent to the receiver-stimulator package and used to modulate the amplitude of a train of balanced-biphasic pulses (D). Adapted from Wilson (2006).

At a basic level, the ACE and SPEAK strategies code pitch in two ways: (1) a place code, in which the stimulation of basally- and apically-situated electrodes is used to indicate the presence of high and low frequency sounds respectively, in accordance with the tonotopic organisation of the cochlea, and; (2) a temporal code that relies upon the envelope-based amplitude modulation of a train of balanced-biphasic pulses and activation of a variable number of SGNs.

2.3.2 Place Coding

Limitations in the processing of place-based pitch cues exist from the initial stage of processing. The filterbanks involved in CI processing strategies are markedly different to the auditory filters of a normal cochlea, which are non-linear, level-dependent and have continuous centre frequencies. The number of largely independent filters in normal hearing is approximately 39 covering the frequency range between 50 Hz and 15 kHz, 28 of which exist within the frequency range in which speech sounds fall (B. C. J. Moore, 2003). By contrast, CI filterbanks are comprised of a smaller number of wide bandpass filters (22 for ACE, 20 for SPEAK) with fixed centre frequencies that cover a more restricted frequency range. Low-order harmonics may not be fully resolved by these wide bandpass filters, making it difficult for listeners to derive the pitch of harmonics and/or extract the F0 of complex sounds. Laneau, Wouters and Moonen (2004) investigated the pitch ranking performance of four unilateral CI users (Nucleus CI24; ACE) in the presence of only place-based pitch cues using pairs of synthetic harmonic complexes similar to stylized vowels. Participants were tested using an ACE filterbank and three experimental filterbanks designed to improve the resolution of low-frequency harmonics. The role of place-based pitch cues was assessed by low pass filtering the output of each bandpass filter using a cutoff frequency of 10 Hz to remove any temporal cues. Following the removal of temporal pitch cues, participants were unable to rank F0 using the ACE filterbank, even when stimuli differed by more than 20 semitones (~1.7 octaves). Performance with the experimental filterbanks was significantly better than with the ACE strategy, although F0 differences of around one octave were required for perfect performance using place-cues alone. With the re-introduction of temporal-pitch cues performance with the ACE filterbank increased and there was no significant difference in performance between the various filterbanks. This suggests that the ACE filterbank does not allow for the transmission of place-based pitch information, at least for F0 of the synthetic vowels used in this study.

The delivery of place-pitch cues is limited by the nature of direct electrical stimulation. The number of independent sites of stimulation is physically limited by the number, size and spacing between intracochlear electrodes. Nucleus CI24 arrays have 22 stimulating electrodes with a maximum inter-electrode spacing distance of 0.75 mm (see *Figure 2.9*).

Pitch perception in further limited by overlaps in the electrical currents generated at adjacent (and more distant) electrodes (e.g. Q.J. Fu & Nogaki, 2005). Overlapping electrical currents are unavoidable as intracochlear arrays are surrounded by the highly conductive fluid that fills scala tympani (Wilson & Dorman, 2008). Current evidence suggests only 4 to 8 independent sites of stimulation are available, even for arrays with up to 22 electrodes (Fishman, Shannon, & Slattery, 1997; Friesen, Shannon, Baskent, & Wang, 2001; Kiefer, Von Ilberg, Hubner-Egener, Rupprecht, & Knecht, 2000).

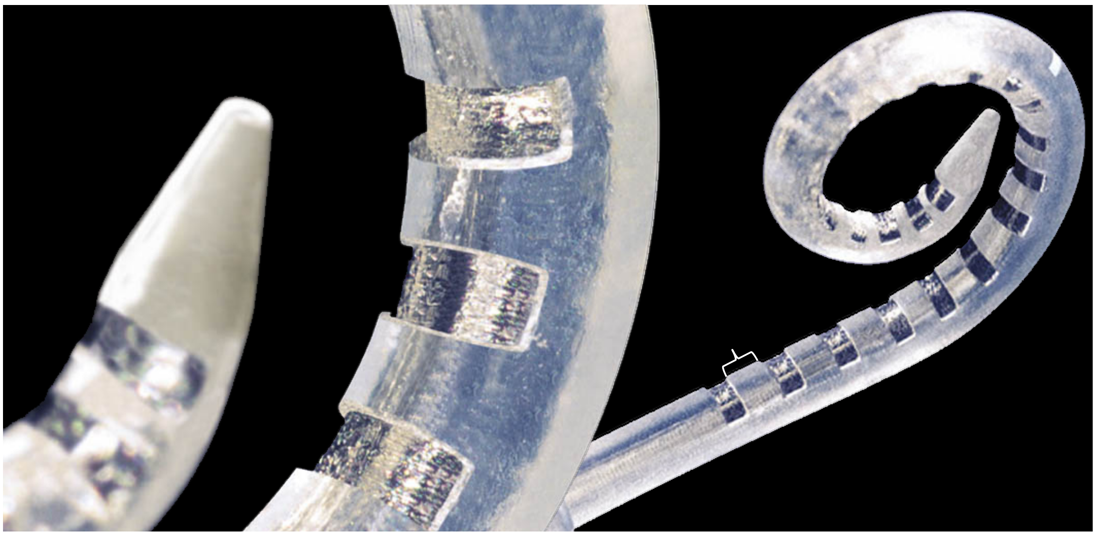

Figure 2.9: **The Nucleus Contour™ Advance electrode array.**

Nucleus 24 intracochlear electrode arrays physically maximise spatial specificity of stimulation through the use of; half-banded electrodes that face the modiolus; and pre-curved contour and contour advance array that hug the modiolus. The Nucleus Contour Advance array has a diameter of that ranges from 0.8mm the base to 0.5mm at the apex. The distance between electrodes is a maximum of 0.75mm for basal electrodes, but decreases at the apex. The distance between electrodes remains constant for the straight and Contour™ arrays ("Cochlear Product Photos," 2008).

A host of biological variables can also limit the ability of CI users to use place cues in their perception of pitch including the density, and distribution of SGNs relative to the electrode array and/or the pathophysiology of the hearing loss (Incesulu & Nadol, 1998; Miura, Sando, Hirsch, & Orita, 2002; Nadol & Eddington, 2006; Schuknecht & Gacek, 1993; Zimmermann, Burgess, & Nadol, 1995). In certain cases, electrodes may also be removed from the device MAP during programming, due to pitch reversals, electrode short-circuits, or facial nerve stimulation, further reducing the total number of potential stimulation sites.

2.3.3 Temporal Coding

Pitch cues in electrical hearing are also provided in the temporal domain. Temporal pitch cues in electric hearing can be made available through: (1) changes in the rate of the stimulating pulse train, and; (2) fluctuations in the amplitude of the stimulating pulse train. As the SPEAK and ACE strategies use fixed-rate pulse trains, the former does not occur and pitch cues are only available via amplitude modulations in the stimulating pulse train. Multiple studies indicate that CI-users are unable to accurately discriminate pitch differences at rates greater than around 300 Hz (Kong, Deeks, Axon, & Carlyon, 2009; McKay, McDermott, & Clark, 1994, 1995; Zeng, 2002), thus many CI users would have difficulty discriminating temporal pitch cues for stimuli with a fundamental frequency (F0) above middle-C (261.63 Hz) (Looi, 2008; Zeng, 2002). The accuracy of temporal pitch cues is also affected by a range of factors including: sufficient modulation depth (Geurts & Wouters, 2001; McKay et al., 1994, 1995); alignment of the phase of the pulse train across the electrode array (Geurts & Wouters, 2001); and a high sampling rate (McKay et al., 1994, 1995). An in-depth explanation of these factors is beyond the scope of this thesis. For further information see McDermott (2004) for a review.

As mentioned in the previous section, filterbands in current speech processing strategies are often too wide to resolve the individual harmonics of many sounds, thus recipients must rely upon the periodicity of unresolved harmonics when extracting the F0 of sounds. However, not all of the periodicity information is presented to the CI recipient, as current speech processing strategies discard the majority of the temporal fine structure (TFS). Although unimportant for speech recognition in quiet, TFS plays an important role in speech understanding in background noise (for reviews see B. C. J. Moore, 2008 and; Plack & Oxenham, 2005) and musical pitch perception (Smith et al., 2002).

2.3.4 The Dissociation of Place and Temporal Pitch Cues

One of the major differences between the pitch coding in CIs and that of NH is a lack of spectro-temporal integration. The insertion depth of Nucleus 24 electrode arrays is restricted to the most basal 1½ turns of the cochlea (a depth of 25 - 28 mm), with electrical stimulation representing the entire speech frequency range being presented to the adjacent SGN population. It has been suggested that a mismatch between the electrical place of stimulation and biological CF may affect the accuracy of pitch percepts (Dorman, Loizou, & Rainey, 1997; Faulkner, Rosen, & Stanton, 2003; Q. J. Fu & Shannon, 1999). However, recent research from adult CI recipients and NH listeners using spectrally shifted speech suggest that the central auditory nervous system makes adjustments to reduce this place-CF mismatch and restore a more-normal quality to speech perception (Q. J. Fu, Nogaki, & Galvin, 2005; McDermott et al., 2009; Reiss, Gantz, & Turner, 2008; 2007).

Regardless, CI users may still give place and temporal codes different weightings, making judgements using the more consistent and reliable cue. In accordance with this, if the pitch information provided via the temporal and place mechanisms differs, the user’s ability to perceive pitch will be affected. See McDermott (2004) for a detailed review.

2.3.5 Outcomes for Cochlear Implant Users

Current CIs do not provide users with the same pitch resolution as NH listeners. Research has consistently shown that adult CI users perform significantly worse than NH listeners and HA users with bilateral severe to profound hearing loss on tasks of pitch discrimination, pitch ranking and song recognition (see Looi, 2008 and; McDermott, 2004 for a review).

The majority of research into the pitch perception abilities of child CI users has involved song recognition tasks (Mitani et al., 2007; Nakata et al., 2005; Vongpaisal, Trehub, & Schellenberg, 2006, 2009; Vongpaisal, Trehub, Schellenberg, & Papsin, 2004). A summary of details of such studies is available in Table 2.2. Across all studies, stimuli were at least

Study	Participants	Stimuli	Results
Vongpaisal et al. (2004)	10 prelingually deafened CI users (*M* = 12.4 years old; device and strategy not reported). An age-matched sample of NH children (n not reported).	Four different renditions of 14 familiar melodies including: an original recording; an instrumental version (original without vocals); a synthesised piano version of the melody, and; a drum and bass version.	NH listeners were more accurate at correctly recognising the target songs than CI users for all four rendition types. CI users were unable to correctly identify melodies using cues available in the simple piano rendition.
Nakata et al. (2005)	13 prelingually deafened CI users (*M* = 6.7 years old, device and strategy not reported).	14 children's television theme songs with three different renditions: an original recording; an instrumental version; and a synthesised flute rendition of the melody.	Performance exceeded chance levels for the original song versions but not for the instrumental or synthesised flute versions.
Vongpaisal et al. (2006) Experiment 2	10 CI users (*M* = 12.67 years old, Nucleus CI22 with SPEAK or Nucleus CI24 with ACE or SPEAK strategy. 10 age-matched NH children.	14 pop songs with three different renditions: an original recording; an instrumental version, and; and a synthesised piano rendition of the melody.	The NH children scored significantly higher than their CI counterparts for all three renditions. Performance for the CI group was above chance for the original and instrumental renditions, but not the piano rendition of the melody.
Mitani et al. (2007)	17 congenitally deafened CI users (*M* = 6.5 years of age; 15 Nucleus CI24- 12 ACE, 3 SPEAK; 2 Advanced Bionics implants-1 MPS, 1 SAS strategy).	14 television theme songs with three different renditions: an original recording; an instrumental version, and; a synthesised flute rendition of the melody.	CI users performed above chance levels for the original renditions, but below chance levels for the instrumental and flute renditions of the melody.
Vongpaisal et al. (2009) *Study required greater song familiarity for participant inclusion than previous studies.	17 CI users (*M* = 8.4 years old, Nucleus CI24, ACE or SPEAK). 39 NH children between 4 and 6 years of age (*M* = 5.2 years old).	10 children's television theme songs with three renditions: original (with vocals); instrumental; and a synthesised flute rendition of the melody.	Unlike previous studies, 10 of the 17 CI users performed above chance levels (25% correct) for the instrumental and synthesised flute renditions of the melody. CI users still performed significantly poorer than their NH counterparts.

Table 2.2: Results of song recognition research involving child CI users. Stimulus selection methods varied between studies, and not all songs were presented to each participant. Refer to the original publications for further details.

three different renditions of the familiar songs, including: an original commercial recording with vocals; an instrumental version without vocals; and a synthesised piano or flute version of the main melody. Overall, child CI users scored significantly lower on melody recognition tasks for all three rendition types relative to their NH counterparts, obtaining the lowest scores when assessed using the instrumental and synthesised melody renditions (Vongpaisal et al., 2004, 2006, 2009). Recognition of instrumental and synthesised melody renditions appears to be more dependent upon rhythm and timing information. Although child CI users (*n* = 17) from Vongpaisal et al. (2009) scored at above chance levels (25% correct) for all three rendition types, they scored at similar levels for both instrumental and synthesised melody renditions, indicating an inability to use the additional pitch information present in instrumental renditions to improve their song recognition accuracy (see *Figure 2.10*).

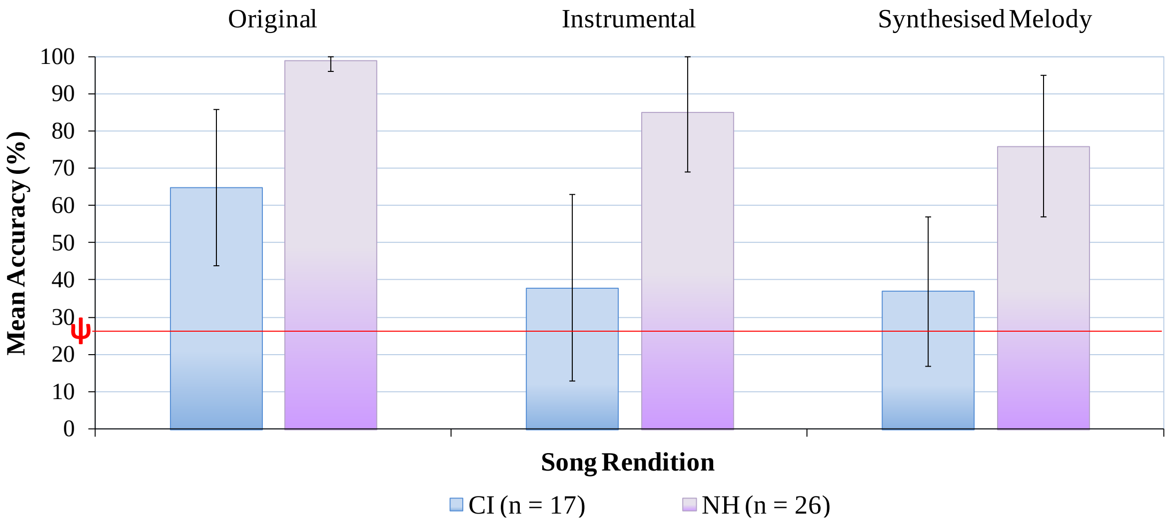

Figure 2.10: **Summary of song recognition results from Vongpaisal et al. (2009).**
ψIndicates the level of chance performance.
Error bars represent ± 1 standard deviation from the mean.

Child CI users also have poorer pitch discrimination abilities than their NH peers (Sucher, 2007; Vongpaisal et al., 2006). Vongpaisal et al. (2006) compared the pitch discrimination abilities of 12 prelingually deafened CI users (8 - 19 years old) and 12 NH 8-year-olds. Stimuli were sequences of five equal-duration (200 msec), equal-amplitude piano tones with inter-tone gaps of 350 msec. Standard sequences consisted of a single repeating tone (C4 = 262 Hz). Altered sequences were identical except that the fourth tone was displaced upward in pitch by 7, 6, 5, 4, 3, 2, 1, 0.5 or 0.25 semitones. Participants were required to detect the presence or absence of a pitch change in the sequence. Accuracy scores were calculated by subtracting ‘false alarm’ rates from ‘correct hits.’ CI children discriminated pitch significantly less accurately than their NH counterparts across all interval sizes (see *Figure 2.11*). Amusic adults from Hyde & Pertetz (2004) were more successful at discriminating pitch for a 1 semitone interval size (M = 0.9) than CI users (M = 0.61), even though the task used to assess CI users was easier. Sucher (2007) compared the performance of 11 child CI users and 11 age-matched NH peers on a modified version of the tonal subtest of the Primary Measures of Music Audiation (PMMA) (Gordon, 1979). Stimuli were 40 pairs of arrhythmic short melodies (2 to 5 notes) and participants were required to state whether two melodies in a pair were the same or different. CI children scored significantly poorer (M = 78.0%) than their NH counterparts (M = 94.8% correct). Overall, these results indicate that the pitch discrimination abilities of CI users are considerably poorer than those of their NH counterparts.

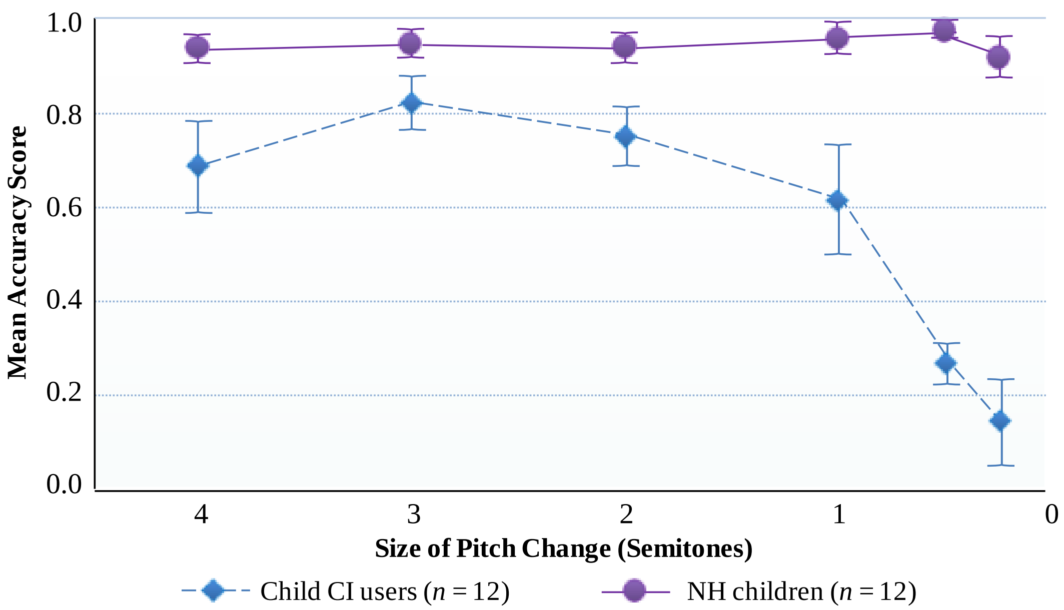

Figure 2.11: **Comparison of the pitch discrimination abilities of normal-hearing and CI children.** Accuracy scores were calculated by subtracting ‘false alarm’ rates from ‘correct hits.’ Adapted from Vongpaisal et al. (2006)

Investigations into the pitch ranking abilities of CI users have been restricted to adult participants (Looi, McDermott, McKay, & Hickson, 2004, 2008a, 2008b; Sucher &

McDermott, 2007). Sucher and McDermott (2007) compared the pitch ranking ability of 10 NH adults and 8 CI users (Nucleus CI24 or CI22; SPEAK strategy). Stimuli were pairs of sung-vowels that differed in their F0 either 1 semitone, or a ½ octave (F0 range 98 - 740 Hz). Participants were required to indicate which of the two notes was higher in pitch (first or second). As expected, CI users scored significantly lower than their NH counterparts, performing at chance levels for the one semitone interval size. Looi and colleagues (2008b) found similar disparities between the performance of 15 CI users (Nucleus CI24 or CI22; ACE or SPEAK) and 15 HA users with severe-profound hearing loss. The stimuli were as per Sucher and McDermott (2007) with interval sizes of 1, ½, or a ¼ of an octave (12, 6 and 3 semitones respectively). As expected, the HA group scored significantly higher than the CI group for all three interval sizes, the CI group scoring at chance levels for the ¼ octave interval. Looi et al. (2008a) used the same pitch ranking task to assess the performance of nine subjects on the waiting list for a CI prior to (with HAs), and three months, after implantation. Post-implantation score were significantly lower for the 1 and ¼ octave interval sizes and were at chance levels for the ¼ octave subtest. Overall, the results of Looi et al. (Looi et al., 2008a, 2008b) indicate that the salience of pitch cues available to current CI users is poor relative to those available to HA users with severe-profound SNHL.

Despite the limitations in the pitch perception abilities of CI users, child CI users provide favourable appraisals of music (Gfeller et al., 1998; Nakata et al., 2005; Sucher, 2007; Vongpaisal et al., 2004), obtaining considerable pleasure from it, unlike their postlingually deafened adult counterparts (Gfeller et al., 2000; Looi & She, in press).

2.4 Advantages of Bimodal and Electroacoustic Stimulation

Through the stimulation of residual acoustic hearing, BMS is thought to provide users with a more accurate representation of the F0 and low-order harmonics than they would likely receive using a CI only. The vast majority of studies investigating the effect of BMS and EAS on pitch perception have only examined the performance of postlingually deafened adults (Dorman, Gifford, Spahr, & McKarns, 2008; Gantz et al., 2006; Gfeller, Olszewski, Turner, Gantz, & Oleson, 2006; Gfeller et al., 2007; Kong et al., 2004; Stewart, 2006; Sucher & McDermott, 2009).

A number of studies have investigated the effect of BMS on melody recognition tasks (Dorman et al., 2008; Kong et al., 2004; Sucher & McDermott, 2009). Stimuli in these studies lacked timing and rhythmic information[1] hence pitch was the sole cue for melody recognition. Kong et al. (2004) investigated the melody recognition abilities of five adult users of BMS, who were assessed in CI-alone, HA-alone and BMS conditions. Despite providing little to no useful speech recognition, participants scored an average of 45% correct using their HA-alone, 17% points higher than in the CI-alone condition. Scores for the HA-alone and BMS conditions were not significantly different. The same pattern of results has been replicated in similar studies (Dorman et al., 2008; Sucher & McDermott, 2009) (see Table 2.3). In summary, although their residual hearing may not support useful word recognition, the additional pitch cues provided by a contralateral HA can enhance melody recognition in adult users of BMS.

		Mean % Melodies Correct		
	n	BMS	CI-alone	HA-alone
Dorman et al. (2008)	15	71.2	52.0	70.6
Sucher & McDermott (2009)	9	~73.0	~46.0	~74.0

Table 2.3: Summary of melody recognition performance of BMS users.

Although within-group comparison studies indicate that BMS allows for improved pitch perception to a CI-alone, the results of between-group comparisons are unclear. The only between-group comparison study was performed by Dorman et al. (2008) who compared the pitch perception abilities of adult users of BMS (n = 15) to a sample of “high-performing” users of a unilateral CI (n = 65) using an arrhythmic melody recognition task. Results indicated that there were no significant differences between the mean melody recognition

[1] Eliminated through the use of equal-duration notes.

scores of each group. However, the proportion of BMS users who scored ≥ 85% correct on the melody recognition task (53%) was significantly greater than the proportion of CI-only users who scored ≥ 85% correct on the melody recognition task (11%).

Similar comparisons using EAS indicate that the performance of Nucleus Hybrid users is considerably superior to electric-only stimulation via a long-electrode CI (Gantz et al., 2006; Gfeller et al., 2006; 2007). Gfeller et al. (2007) reported that the ability of Hybrid L24 users (n = 4) to recognise instrumental renditions of popular songs was significantly better than that of users of long-electrode CIs (n = 39). They also reported that Hybrid L24 users (n = 13) ranked the pitch of puretones (1, 2, 3 and 4 semitone interval sizes) more accurately than adult users of traditional CI systems (n = 101), although both groups scored significantly poorer than NH listeners (n = 21).

Whether the pitch perception abilities of prelingually-deafened child CI users improve with BMS is uncertain. The only study known to the author investigating the pitch perception abilities of children using BMS is an unpublished master's thesis by Sucher (2007), who assessed the performance of this group (n = 7; M = 11.8 years old; Nucleus CI22 and CI24, SPEAK or ACE) on the tonal subtest of the PMMA. Participants were assessed using their CI-alone and BMS. Unlike adults in previous studies, there were no significant differences between the CI-alone and BMS scores. However, Sucher noted that the children's residual hearing (M ≥ 90 dBHL above 250 Hz) may have been too poor to support accurate pitch discrimination, and participants may have relied upon information from their CIs.

Evidence in support of this comes from El Fata et al. (2009), who investigated the role of residual low-frequency hearing in the melody recognition abilities of adult users of BMS. Stimuli were well known songs: an original recording with vocals; or an instrumental rendition. All stimuli contained rhythm and timing information. Participants were assessed in CI-alone, HA-alone and BMS conditions, and were subsequently separated into two groups according to their median PTAs (0.125, 0.25, 0.5 and 1 kHz). Group I (n = 8) had median PTAs of < 85 dBHL and group II (*n* = 6) had median PTAs of ≥ 85 dBHL. For vocal and instrumental stimuli, group I scored significantly higher in the BMS than the CI-alone condition (see Table 2.4). Scores for the BMS and HA-alone conditions were not significantly different for either vocal or instrumental renditions, consistent with the results of other studies (Dorman et al., 2008; Kong et al., 2004; Sucher & McDermott, 2009). In contrast, it subjects in group II showed no bimodal benefit, and scored significantly higher in the CI-alone condition than the HA-alone condition for vocal stimuli, and scored poorly for instrumental stimuli, with no significant difference in performance between the CI-alone and BMS scores (see Table 2.4). It appears that group II were unable to utilise the acoustic information provided by a contralateral HA, probably due to insufficient residual hearing function, and relied upon information provided via their CI for melody recognition.

	% Melodies Correct - With Lyrics			**% Melodies Correct - Instrumental**		
	BMS	CI-only	HA-only	BMS	CI-only	HA-only
Group I	81.5	71.5	72.3	57.2	38.8	59.7
Group II	69.8	79.8	30.8	26.3	28.3	26.3

Table 2.4: Select results from El Fata et al. (2009).

Group II adults from El Fata et al. (2009) and child users of BMS from Sucher's (2007) study had similar mean low-frequency hearing thresholds (see *Figure 2.12*) supporting the hypothesis that limited residual hearing limited bimodal benefit for both groups. However, the level of functional deficit resulting from cochlear hearing loss can vary markedly between individuals with similar unaided puretone thresholds. An alternative explanation for the lack of bimodal benefit for melody recognition seen in Sucher's (2007) study is that limited exposure to auditory stimuli may have impaired their central auditory development. This may have restricted their utilisation of information provided by via a contralateral HA, even when the signal was audible.

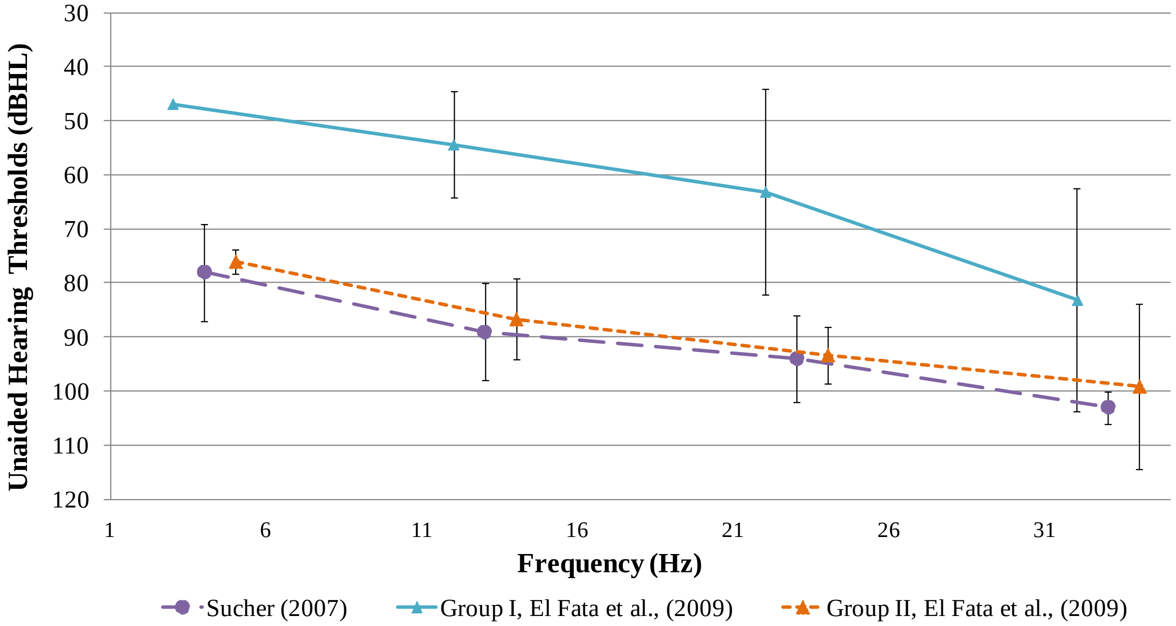

Figure 2.12: **Mean unaided low-frequency hearing thresholds for participants in Sucher (2007) and El Fata et al. (2009).**

Error bars represent ± 1 standard deviation from the mean.

Overall, evidence indicates that BMS and EAS allow for an improved perception in the quality of music, at least in postlingually deafened adults. In the case of monaural EAS advantages are known to be due to the provision of additional low-pitch information via acoustic residual hearing, low-frequencies up to a certain cut-off being excluded from Hybrid users' MAPs (Gantz et al., 2006; Gfeller et al., 2006, 2007). In the case of BMS, the quality of the pitch information provided via acoustic residual hearing, and the ability of users to utilise this information is yet to be detailed in full.

3 Speech Recognition

Although current CI processing strategies do not provide CI users with an accurate perception of pitch, they have been successful in their original goal: conveying information sufficient for speech perception (see Wilson & Dorman, 2008 for a review). Current strategies allow for good open-set speech recognition in quiet (Blamey et al., 2001; Eisenberg, Kirk, Martinez, Ying, & Miyamoto, 2004; Svirsky & Meyer, 1999). However, the performance of CI users in situations where there is background noise is considerably poorer, due to the poor salience of pitch cues accessible via a CI (Qin & Oxenham, 2003, 2005; Stickney, Assmann, Chang, & Zeng, 2007; Stickney, Zeng, Litovsky, & Assmann, 2004). BMS has been shown to improve speech recognition in difficult listening situations through the provision of low-frequency pitch cues which can be used in the segregation of competing sounds (J. E. Chang et al., 2006; Kong & Carlyon, 2007; Kong et al., 2004), and provide access to binaural mechanisms that enhance speech recognition in noise (Beijen et al., 2008; Ching et al., 2001, 2004, 2006, 2007; Ching, van Wanrooy, Hill, & Dillon, 2005; Mok et al., 2007).

3.1 Outcomes for Cochlear Implant Users

3.1.1 Speech Recognition in Quiet

In general, the open-set speech recognition performance of CI users in quiet listening situations is equivalent to that of HA users with severe-profound hearing loss (Blamey et al., 2001; Boothroyd & Eran, 1994; Eisenberg et al., 2004; Flynn, Dowell, & Clark, 1998; Fukuda et al., 2003; Svirsky & Meyer, 1999). Current implant systems allow for monosyllabic word recognition scores of between 50% and 60% correct, however, outcomes can vary widely, some participants scoring at ceiling levels and others near zero percent correct (see Wilson & Dorman, 2008 for a review). Poorer performers are often limited by pathophysiological factors and/or prolonged duration of deafness resulting in cross-modal plasticity[2] and an inability to effectively use the signal provided by a CI (Blamey et al., 1996; Lee et al., 2001; D. R. Moore & Shannon, 2009). As much as 40% of the individual variations in performance is due to unknown factors (Blamey et al., 2001).

On average, after 12 to 18 months of device usage, children using cochlear implants obtain similar open-set speech recognition scores similar to those of child HA users with severe hearing losses (Blamey et al., 2001; Eisenberg et al., 2004; Rotteveel, Snik, Vermeulen, Cremers, & Mylanus, 2008; Svirsky & Meyer, 1999). Recent estimates indicate that a child is 75% likely to obtain better speech recognition using a CI than a HA in an ear with a PTA of > 72 dBHL (Leigh, Hollow, & Dowell, 2009). Blamey et al. (2001) compared the speech recognition abilities of prelingually deafened HA users (*n* = 40) and CI users (*n* = 47; Nucleus CI22, SPEAK) using the CNC word lists and BKB-A sentences in quiet. They reported that on average, a CI user was found to perform at the same level as a HA user with a PTA of approximately 78 dBHL. Consistent with this, Eisenberg et al. (2004) reported no significant difference between the HINT sentence recognition scores of a group of child CI users (*n* = 66) and a group of bilateral HA users (*n* = 29) with a mean PTA of 78.2 dBHL. However, they noted that when tested in noise at a 5 dB signal-to-noise ratio (SNR), CI users experienced considerably more difficulty on the HINT sentence task than HA users.

3.1.2 Speech Recognition in Noise

NH listeners use differences in the F0 and temporal fine structure information (TFS) to segregate competing sound sources (see Oxenham, 2008 for a review). This information allows for improved speech recognition in the presence of complex, fluctuating background noise (for example, a competing talker) by providing additional speech information that, in combination with a listener’s knowledge of spoken language, may be used to ‘fill in’ any

[2] Cross-modal plasticity refers to the re-allocation of the processing power of neurons from an area that normally processes information pertaining to one modality (e.g. audition), to another modality (e.g. touch or sight). This may occur following a period of stimulatory deprivation (e.g. long-term deafness).

'gaps' in the audible speech stream. The superior performance of NH listeners in fluctuating noise, relative to steady-state noise (SSN), is known as 'masking release.'

CI users do not exhibit masking release, nor are they able to use F0 differences to separate target speech from a competing talker (Stickney et al., 2004). Stickney et al. (2004) assessed the speech recognition performance of 25 NH listeners and 5 adult CI users (Nucleus CI22 or CI24; SPEAK). Stimuli were IEE sentences, presented monaurally in either their natural state (all participants), or through 8- and 4- channel CI simulations (NH listeners) at 0, 5, 10, 15 and 20 dB SNRs. Target sentences were spoken by a male talker in the presence of SSN, or one of three competing talkers: the male target sentence talker (F0: M = 108 Hz); a different male talker (mean F0 = 136 Hz); or a female talker (F0: M = 219 Hz). As expected, when listening to natural sentences at SNRs as low as 0 dB the NH group: (1) exhibited significant 'masking release,' scoring higher in the presence of speech maskers than in the presence of SSN, and; (2) scored higher when the competing talker had a different F0 to the target sentences, indicative of their ability F0 differences to separate competing sounds. In contrast, no masking release was observed in either the CI group, or the NH group listening via either the 4- or 8-channel CI simulation. The performance of CI users and NH adults listening via a CI simulation also failed to improve when the single-talker masker was different to that of target speech. In general, the consensus is that the temporal representation of the F0 used in current speech processing strategies does not provide sufficient information to allow for the segregation of sounds from competing sources using F0 cues, nor does it allow for 'masking release' (Qin & Oxenham, 2003, 2005; Stickney et al., 2004, 2007).

3.2 Potential Advantages of Bimodal Stimulation

3.2.1 Speech Perception in Quiet

The monosyllabic word recognition scores of CI users improve significantly following the addition of a contralateral HA (Beijen et al., 2008; Ching, 2001, 2004, 2005, 2006; Dunn et al., 2005; Mok et al., 2006). However, the greater redundancy of sentences appears to be sufficient to eliminate any performance gap between users of BMS and users of a unilateral CI, in auditory-alone test conditions (Dorman et al., 2008; Gifford, Dorman, McKarns, & Sphar, 2007; Gifford, Shallop, & Peterson, 2008). Mok et al. (2006) assessed the CNC word recognition performance of 14 adult CI users (Nucleus CI24) in CI-alone, HA-alone and BMS conditions. Scores for 12 of the 14 participants improved using BMS, although this improvement was only significantly different to their CI-alone performance in four cases. The results of information transmission analyses showed that BMS allowed for a better perception of low-frequency phonemes, in part due to greater transmission of information regarding the place and manner of articulation compared with a CI or HA alone (Ching et al., 2001). Gifford et al. (2008) compared the performance of unilateral CI-users (n = 162), BMS users (n = 36), and HA-only users (n =76) with steeply sloping severe-profound hearing loss on the CNC word lists in quiet. Results showed that the BMS group (M = 71.8% correct) scored significantly higher than CI-only (M = 55.7%) and HA-only groups (M = 32.8%).

3.2.2 Advantages for Speech Recognition in Noise

Bimodal stimulation improves speech recognition in noise by providing low-frequency pitch cues that aid in the segregation of competing sounds (J. E. Chang et al., 2006; Kong & Carlyon, 2007; Kong et al., 2004), and enabling the spatial segregation of sound via binaural processing mechanisms (Beijen et al., 2008; Ching et al., 2001, 2004, 2005, 2006, 2007; Mok et al., 2007).

3.2.2.1 Low-frequency Pitch Cues and the Segregation of Competing Sounds

The additional pitch cues provided via acoustic residual hearing in BMS allows for the improved segregation of the F0 of competing talkers, and ‘masking release.’ (J. E. Chang et al., 2006; Dorman et al., 2008; Gantz et al., 2006, 2009; Gfeller et al., 2007; Gstoettner et al., 2008; Kong & Carlyon, 2007; Kong et al., 2004). Kong et al. (2004) assessed the IEE sentence recognition abilities of adult users of BMS (*n* = 4). Target speech was spoken by a male talker, competing sentences by a female or a different male talker. Participants were assessed in SNRs of 0, 5, 10, 15 and 20 dB using their HA-alone, CI-alone or BMS. Speech recognition scores were negligible for the HA-only condition. Participants scored significantly higher in the BMS condition than the CI-only condition in the 10 and 15 dB SNRs. In the BMS condition participants also exhibited significant masking release, indicated by an average increase in score of 21 % points when the masker was changed from male talker to a female talker. In contrast, in the CI-only condition there was no significant 'masking release.' Overall, results indicate that the additional pitch information provided via a contralateral HA allows BMS users to benefit from 'masking release.'

The role of low-frequency acoustic information in the enhancement of the speech in noise recognition abilities of BMS users has been examined in recent CI simulation studies (J. E. Chang et al., 2006; Kong & Carlyon, 2007; Qin & Oxenham, 2006). Chang et al. (2006) assessed the sentence recognition performance of 16 NH participants listening to a CI simulation with low-pass filtered acoustic speech presented to the contralateral ear. The adaptive form of the HINT sentence recognition task was used to determine the SNR required for 50% correct scores ($SNR_{50\%}$). In part one of the experiment, the low-pass filter (LPF) cut-off for the acoustic speech was set at 250, 500, or 1000 Hz. Participants were assessed in LPF-speech-alone, CI-alone and EAS simulation conditions. For LPF-speech-alone, maximum recognition scores were ≤ 11% precluding the measurement of $SNR_{50\%}$. For the CI-alone condition $SNR_{50\%}$ was approximately 10 dB. In the EAS condition, $SNR_{50\%}$ decreased (improved) significantly for all three LPF conditions by between 10 - 15 dB. $SNR_{50\%}$ decreased (improved) with increasing LPF cut-off frequency, indicating that the presence of otherwise unintelligible low-frequency information significantly improved CI speech recognition in noise. In part two of the experiment, participants were assessed in a range of listening conditions including, EAS[3], BMS[4], and a BMS simulation with acoustic

[3] Acoustic speech was low-pass filtered using a cut-off frequency of 500 Hz.

speech high-pass filtered (HPF) above 4 kHz. Performance in the EAS and BMS conditions was similar indicating that benefit was not dependent upon the interaction of low- and high-frequency information within a single ear. The addition of HPF speech to the CI simulation produced no significant improvement in $SNR_{50\%}$ indicating that low-frequency information was crucial to bimodal benefit for speech recognition in noise. Overall, the results of experiments using BMS users and CI simulations indicate that increased access to low-frequency F0 information allows for improved segregation of target speech from competing talkers (J. E. Chang et al., 2006; Kong & Carlyon, 2007; Kong et al., 2004).

3.2.2.2 Effects of Binaural Stimulation in relation to Spatial Unmasking

'Spatial unmasking' is the improvement in speech recognition in noise when target speech and masking noise are spatially separated compared to when the speech and noise arrive from the same source (Mok et al., 2007). Contributing to spatial unmasking are: the head shadow effect[5], "binaural redundancy[6]", and "binaural squelch[7]." Two of these mechanisms are used by adult users of BMS to improve speech recognition in noise (Beijen et al., 2008; Ching et al., 2001, 2004, 2005, 2007; Dunn et al., 2005; Luntz et al., 2005; Mok et al., 2007; Mok, Galvin, Dowell, & McKay, 2010).

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4 See footnote '4' on the previous page.

5 The head shadow effect is caused by interactions between the acoustic environment and the head that result in a between-ear difference in SNR. Selective attention to information from the ear with the better SNR results in an improvement in speech perception equal to a 3dB increase in the SNR for NH listeners (Dillon, 2001).

6 Binaural redundancy relies on the comparison of acoustic information arriving at each ear. Information from each ear is combined and used in conjunction with a listener's linguistic repertoire to fill 'gaps' in the speech stream. This provides an average gain in speech recognition performance equivalent to a 1 - 2dB increase in the SNR in NH listeners (Dillon, 2001).

7 "Binaural squelch" comprises a range of central auditory processing mechanisms which improve the effective SNR of a signal in noise by analysing differences in the phase and level of the signals arriving at each ear (Ching et al., 2001). It provides an average gain in speech recognition performance equivalent equal to a 2dB increase in SNR for NH listeners (Dillon, 2001).

Unlike their adult counterparts, child users of BMS exhibit no significant head shadow advantage when the better SNR is on the side of their HA (Beijen et al., 2008; Mok et al., 2006, 2007, 2010). Mok et al. (2007) measured the level of spatial unmasking experienced by users of 9 child users of BMS (Nucleus CI24) and 10 NH children. Participants were required to detect "*/baba/*" in the presence of speech-weighted noise. Both target and masker were initially presented from 0° azimuth (i.e. they were spatially coincident). The masker was then presented from 90° azimuth relative to: (1) the implanted ear, and; (2) the HA ear. The SNR for speech detection was adjusted using an adaptive procedure. The NH group experienced spatial unmasking regardless of the direction of the noise shift (M = 5.6 dB). The BMS group showed significant spatial unmasking only when the CI had the better SNR (M = 3.8 dB), obtaining lower scores when the HA had the better SNR, than when both ears had the same SNR (spatially coincident speech and noise). Mok et al. (2010) reported similar results for a group of 9 child users of BMS. In contrast, adult users of BMS exhibit significant spatial unmasking regardless of which ear has the better SNR (Mok et al., 2006). The head shadow effect is most effective at improving the SNR for high-frequency sounds. It is possible that such cues were inaudible for these groups of BMS users due to their poor high-frequency residual hearing (Mok et al., 2010). Alternatively, it is also possible that speech cues provided via their residual hearing were not sufficient for speech recognition, regardless of whether the non-implanted ear had the better SNR (Mok et al., 2010).

Both adult and child users of BMS benefit from binaural redundancy (Ching et al., 2005, 2006). Ching et al. (2006) assessed the speech recognition performance of 11 adult and 25 child users of BMS. Participants were assessed using the BKB-A sentences in quiet and in spatially co-incident 8-talker babble at a 10 dB SNR, in CI-alone and BMS conditions. Both groups benefited from binaural redundancy cues; adults and children scored 17 and 12 % points higher respectively in the BMS condition.

Neither adult, nor child users of are able to utilise binaural squelch mechanisms to enhance speech recognition in noise (Beijen, Snik, Straatman, Mylanus, & Mens, 2010; Ching et al., 2006). Ching et al. (2006) compared the ability of 15 NH listeners and 9 adult users of BMS (Nucleus CI22 or CI24, ACE or SPEAK) to utilise interaural timing differences. The SNR at which participants recognised 50% of BKA-A sentence keywords ($SNR_{50\%}$) in speech weighted noise was measured in three listening conditions using BMS. In the reference condition, speech and noise were presented at 0° azimuth. In the comparison conditions, a 700µs delay was introduced between the speech and noise tracks and the noise was presented at 90° azimuth on the side of: (1) the HA and; (2) the CI. Unlike the NH group, the $SNR_{50\%}$ of the BMS group did not decrease significantly following the introduction of interaural timing differences. Beijen et al. (2010) examined whether 9 child users of BMS (Nucleus CI24; ACE or SPEAK) were able to use interaural phase differences to reduce the threshold at which they detected a pure tone in 1/3 octave broadband noise. Whereas NH children exhibited an improvement in detection thresholds of 5 dB following the introduction of interaural phase differences (Litovsky, 2005), child users of BMS did not. Overall, these results indicate that current speech processing strategies are unable to reliably code phase information required for the accurate perception of interaural time and phase differences (Beijen et al., 2010; Ching et al., 2006).

In summary, of the three binaural processing mechanisms known to aid speech recognition in noise, only binaural redundancy is thought to be used by child users of BMS, resulting in a mean improvement in SNR of around 2 dB (Ching et al., 2005, 2006).

3.3 Between-Group Comparisons of Unilateral Cochlear Implants Users, and Users of Bimodal Stimulation

Two studies have compared the speech recognition performance of separate groups of unilateral CI users and users of BMS (Dorman et al., 2008; Gifford et al., 2008). Gifford et al. (2008) compared the speech in noise recognition performance of 112 unilateral CI users and 11 users of BMS. The CNC word recognition performance of the overall sample showed a normal distribution, indicating that their scores were representative of the general population of CI users. Participants were assessed using the BKB-Speech-In-Noise Test (BKB-SIN), an adaptive sentence recognition test scored measuring the SNR at which participants correctly recognised 50% of keywords ($SNR_{50\%}$) in the presence of multi-talker babble. Results indicated that there was no significant difference between the mean $SNR_{50\%}$ of the CI-only group (M = 11.4 dB) and the BMS group (M = 8.7 dB).

Similar results were found by Dorman et al. (2008) who assessed the speech recognition in noise abilities of 15 users of BMS and 65 users of a unilateral CI. All participants had CNC word recognition scores of ≥ 50% correct using their normal listening devices. The BMS group had previously exhibited significant bimodal benefit on a range of speech recognition tasks in quiet and noise. Participants were assessed using the AzBio sentences in multi-talker babble (5 and 10 dB SNRs). Mean scores for the BMS and CI-only groups were not significantly different. However, the proportion of BMS users who obtained scores of ≥ 85% correct on the AzBio sentences in noise (10 dB SNR; 33%) was significantly greater than the proportion of CI-only users who obtained scores of ≥ 85% correct (6%).

Overall, these results indicate that although individual CI users may exhibit improved performance on tasks of speech recognition in noise scores following the addition of a contralateral HA, in between-group comparisons, the highest performing unilateral CI users may attain similar levels of sentence recognition in noise performance to their counterparts using BMS (Dorman et al., 2008). However, the proportion of BMS users who obtain the highest scores on a given measure appears to be greater than the proportion of CI-only users who do the same (Dorman et al., 2008).

4 Rationale

Most of the existing research into BMS and EAS has involved postlingually deafened adults. The extent of the potential benefits for children may differ because: (1) prelingually deafened children often lack binaural exposure to high-resolution pitch cues, potentially impeding the development of their central auditory processing abilities; (2) their smaller physical head dimensions make them less likely to benefit from head diffraction effect (Mok et al., 2007); (3) their limited language experience is likely to reduce benefits arising from binaural redundancy (Ching et al., 2005), and; (4) many child CI users have been implanted during ‘critical periods’ in which their cortical plasticity is high, potentially enabling them to adapt differently to electric stimulation.

In addition, research relating to the pitch perception abilities of children using HAs in the literature is scarce. Also, no research investigating the pitch ranking abilities of child or adult users of BMS has been published.

4.1.1 Hypotheses

The purpose of the present study was to compare the performance of children using a unilateral CI (CI-only), BMS, or bilateral HAs[8] (HA-only) on tasks of speech recognition in quiet and noise and a pitch ranking task. It was hypothesised that:

1. For tasks of word recognition in quiet, children who use BMS will score higher than children using a CI-only. HA-only and CI-only users will score at similar levels;

2. For tasks of sentence recognition in quiet, children who use BMS, a CI-only, or HA-only will score at similar levels[9];

3. For tasks of sentence recognition in noise, child users of BMS and HA-only users will score higher than their CI-only counterparts;

4. When ranking pitch, children who use BMS will score higher than those using a CI-only, but not children who use bilateral HAs, and;

5. That the addition of an optimally fitted HA in the non-implanted ear of children using a CI will result in better performance in tests of speech recognition in quiet and noise, and pitch perception.

[8] With severe to profound bilateral SNHL.

[9] Due in part to the increased redundancy of sentences compared to words in quiet.

5 Method

5.1 Ethical Approval

Ethical approval was obtained from the University of Canterbury (UoC) Human Ethics Committee and the New Zealand Multi-region Health and Disability Ethics Committee (HDEC). All procedures undertaken were in accordance with these approvals. Participation in the present study was voluntary and participants were free to withdraw from the study without penalty or impact on their other clinical assessments. The parent/ caregivers of participants provided written consent before any assessments were undertaken.

5.2 Participants

In order to address the hypotheses outlined in the previous chapter, five groups of participants were recruited for this study:

GROUP A: New users of bimodal stimulation (nBM)

GROUP B: Users of a unilateral cochlear implant (CI-only)

GROUP C: Users of bilateral hearing aids (HA-only)

GROUP D: Experienced users of bimodal stimulation (eBM)

GROUP E: Normal hearing (NH) listeners

Group A participants had at least 12 months of experience with their CI. They also had: aidable levels of residual hearing in their non-implanted ear, had not used a HA post-implantation, and were willing to trial a HA in this ear for 3 months. Group B participants had at least 12 months of experience with their CI and did not have aidable levels of residual hearing in their non-implanted ear. Group C participants had bilateral moderately-severe to profound stable sensorineural hearing losses between 1 and 4 kHz and used appropriately fitted hearing aids. These hearing levels were chosen as they are in line with the referral criteria to the pediatric branch of the Southern Cochlear Implant Programme (SCIP; see *Figure 1.8*). Participants in Group C had aided HINT sentence in quiet scores of greater than 60% correct when assessed binaurally. This ensured that they did not meet SCIP CI candidacy criteria (see section 1.4) and would not be implanted during the course of the study. Group D participants had at least 12 months experience using their CI alone and at least 6 months using this in combination with a HA in their non-implanted ear. Group E participants had hearing thresholds that were within normal limits (≤ 20 dBHL at octave frequencies between 250 Hz and 8 kHz).

All participants were between 6 and 18 years old, used spoken English as their first language, and were educated in an oral/aural learning environment. Children scored at least 30% on open-set speech recognition tests performed post-implantation and had stable MAPs that were unlikely to need adjustment during the study.

Participants in groups A - D were recruited via organisations involved in the management of hearing-impaired children. The nBM and CI-only groups were recruited via the SCIP, the HA-only group was recruited via the Advisers on Deaf Children (AODCs) and the eBM group was recruited via the Sydney Cochlear Implant Centre (SCIC). NH participants were recruited via advertisements in the University Bulletin.

Consent rates were very low particularly for the nBM (1/11, 9.1%) and CI-only (8/43, 18.6%) groups, partly due to the long travel times (> 2 hours) required of many candidates. Response rates were higher for the HA-only (7/10, 70%) and eBM (10/31, 32.3%) groups who lived closer to the testing centres. 15 NH listeners consented to participate.

Two eBM participants were withdrawn from the study; one decided to pursue bilateral implants and a second was unable to attend either of the scheduled appointments. Summary statistics for consenting participants are available in Table 5.1. The details of participants in each group are provided in Tables 5.2 - 5.5.

Group	*n*	Chronological Age (Years) *M*	Range	Implantation Age (Years) *M*	*SD*	Device Usage (Months) *M*	Range	PTA Better Ear (0.5, 1 and 2kHz, dB HL) *M*	*SD*
nBM	1	11.46		9.83		19.80		95.0	
CI-only	8	12.92	11 - 14	5.28	2.32	94.17	28 - 134	125.0	0.0
HA-only	6	12.08	10 - 15	N/A		108.59	80 - 135	65.8	15.9
eBM$^{\varphi}$	8	9.25	6 - 13	5.40	2.76	47.62$^{\varphi}$	12 - 86	89.7	12.7
NH	15	12.06	8 - 16	N/A		N/A		10.9	2.3

Table 5.1: Summary statistics for consenting participants.

$^{\varphi}$All eBM users continued to use a HA in their non-implanted ear following switch-on of their CI.

All CI-users in this study used Cochlear Ltd. Nucleus 24 implant systems in combination with either an ESPrit 3G or Freedom processor programmed with the ACE or SPEAK speech processing strategies (see Tables 5.6 - 5.7). All HAs used in this study were multichannel digital BTEs fit using the NAL-NL1 or DSL$_{[i/o]}$ prescriptive formulae using wide-dynamic range compression (WDRC; see Tables 5.8 - 5.9). Individual puretone averages (PTA) was defined as the mean of a participant's unaided thresholds at 0.5, 1, and 2 kHz.

Participants were categorised according to their level of previous musical experience, or Musical Experience Level (MEL) where: '3' represented ≥ 2 years of participation in formal music training and/or classroom music activities; '2' represented < 2 years of participation in formal music training and/or classroom music activities; and '1' represented no participation in formal musical training and/or classroom music activities.

ID	Gender	Age (Years)	Type of Loss	Age of Diagnosis (months)	Level of Hearing Loss at Diagnosis	Gestation Length (weeks)	Pregnancy / Birth Complications	Intrauterine CMV	Hypoxia / Anoxia	Jaundice	Ototoxic Drugs	Abnormal Cochlear Morphology	Eitology	MEL
B001	M	14.24	C	13	Profound (L, R)	41	Y	N	Y	N	N	N	Perinatal Anoxia	2
B002	F	12.73	C, P	8	Profound (L, R)	33	Y	Y	N	N	N	Y	Mondini Aplasia (L, R), CMV	2
B003	M	14.40	U	25	Profound (L, R)	40	N	U	N	N	N	N	Unknown	2
B004	F	12.06	C	17	Profound (L, R)	40	Y	N	N	N	N	N	Unknown, Gestational Diabetes	1
B005	M	13.96	C, P	3	Mild (L), Severe (R)	27	Y	N	Y	N	N	Y	Mondini Aplasia, EVAS (L, R)	1
B006	M	11.57	C, P	8	Moderate-Severe (L, R)	37	N	U	N	N	N	Y	Unknown Genetic (cochlear dysplasia (L, R), low muscle tone, cardiac septal defect)	2
B007	M	13.35	C	1	Profound (L, R)	40	N	U	U	N	N	N	Autosomal Recessive	2
B008	M	11.05	C, P	19	Moderate-Severe (L), Profound (R)	40	N	U	U	N	N	Y	Mondini & EVAS (L, R), Pendred's Syndrome	2

Table 5.2: Participant information for CI-only group.

C = Congenital, P = Progressive, U = Unknown, EVAS = Enlarged Vestibular Aqueduct Syndrome, CMV = Cytomegalovirus.
MEL = Music Experience Level

ID	Gender	Age (Years)	Type of Loss	Age of Diagnosis (months)	Level of Hearing Loss at Diagnosis	Gestation Length (weeks)	Pregnancy/ Birth Comp.	Intrauterine CMV	Hyp/Anoxia	Jaundice	Ototoxic Drugs	Abnormal Cochlear Morphology	Eitology	MEL
A001[ϟ]	F	11.46	C	12	Profound (L), Severe-Profound (R)	40	N	U	Y	N	N	N	Unknown, Mild Hypoxia at birth, Febrile Episodes first year	2
D001	F	9.41	C	6	Severe-Profound (L, R)	27	Y	N	N	Y	Y	N	Unknown Genetic Recessive	2
D002	M	6.90	C	36	Severe-Profound (L), Profound (R)	40	N	N	Y	N	N	N	Unknown Genetic Recessive	1
D003	M	6.38	C, P	28	Profound (L), Moderate-Profound (R)	32	Y	N	Y	Y	N	N	Genetic Recessive, Cx26	1
D004	F	8.48	C	20	Profound (L), Moderate-Severe (R)	29	Y	N	Y	Y	Y	N	Unknown, possible Auditory Neuropathy	1
D006	F	7.44	A, S	9	Moderately-Severe to Profound (L, R)	25	Y	N	Y	Y	N	N	Pneumoccal Meningitis	1
D007	F	11.10	C	21	Moderate-Profound (L), Profound (R)	28	Y	N	Y	N	Y	Y	Mondini Dysplasia, Ototoxicity	2
D008	M	11.40	C	3	Moderate-Profound (L), Profound (R)	33	Y	N	Y	Y	Y	N	Genetic Recessive, Ototoxicity	1
D009	M	12.86	C	39	Moderately-Severe to Profound (L, R)	40	N	N	N	N	N	N	Genetic Recessive, Cx26	3

Table 5.3: Participant information for nBM and eBM groups.

[ϟ]New bimodal user, C = Congenital, U = Unknown, A = Acquired, P = Progressive S = Sudden, CMV = Cytomegalovirus. MEL = Music Experience Level. Participant D005 was withdrawn from the study prior to testing, so their details are not reported here.

ID	Gender	Age (Years)	Type of Loss	Age of Diagnosis (months)	Level of Hearing Loss at Diagnosis	Gestation Length (weeks)	Pregnancy/Birth Complications	Intrauterine CMV	Hypoxia/Anoxia	Jaundice	Ototoxic Drugs	Abnormal Cochlear Morphology	Eitology	MEL
C001	M	13.12	U, P	18	Moderately-Severe to Severe (L, R)	40	Y	N	Y	N	N	N	Unknown	2
C003	F	9.66	U, P	60	Moderate to Severe (L, R)	40	N	N	N	N	N	U	Unknown	2
C004	M	15.02	C	61	Moderate to Severe (L) Profound (R)	40	N	N	N	N	N	U	Autosomal Recessive, Cx26	3
C005	M	11.83	C	38	Severe-Profound (L, R)	40	N	N	N	N	N	U	Autosomal Recessive, Cx26	2
C006	F	9.84	C, P	37	Moderate to Severe (L, R)	40	N	N	N	N	N	Y	EVAS, (L, R)	2
C007	F	11.51	C	33	Moderate (L, R)	40	N	N	N	N	N	N	Unknown	2

Table 5.4: Participant information for HA-only group.

'C' = Congenital, 'U' = Unknown, 'P' = Progressive, 'EVAS' = Enlarged Vestibular Aqueduct Syndrome, CMV = Cytomegalovirus.
MEL = Music Experience Level.

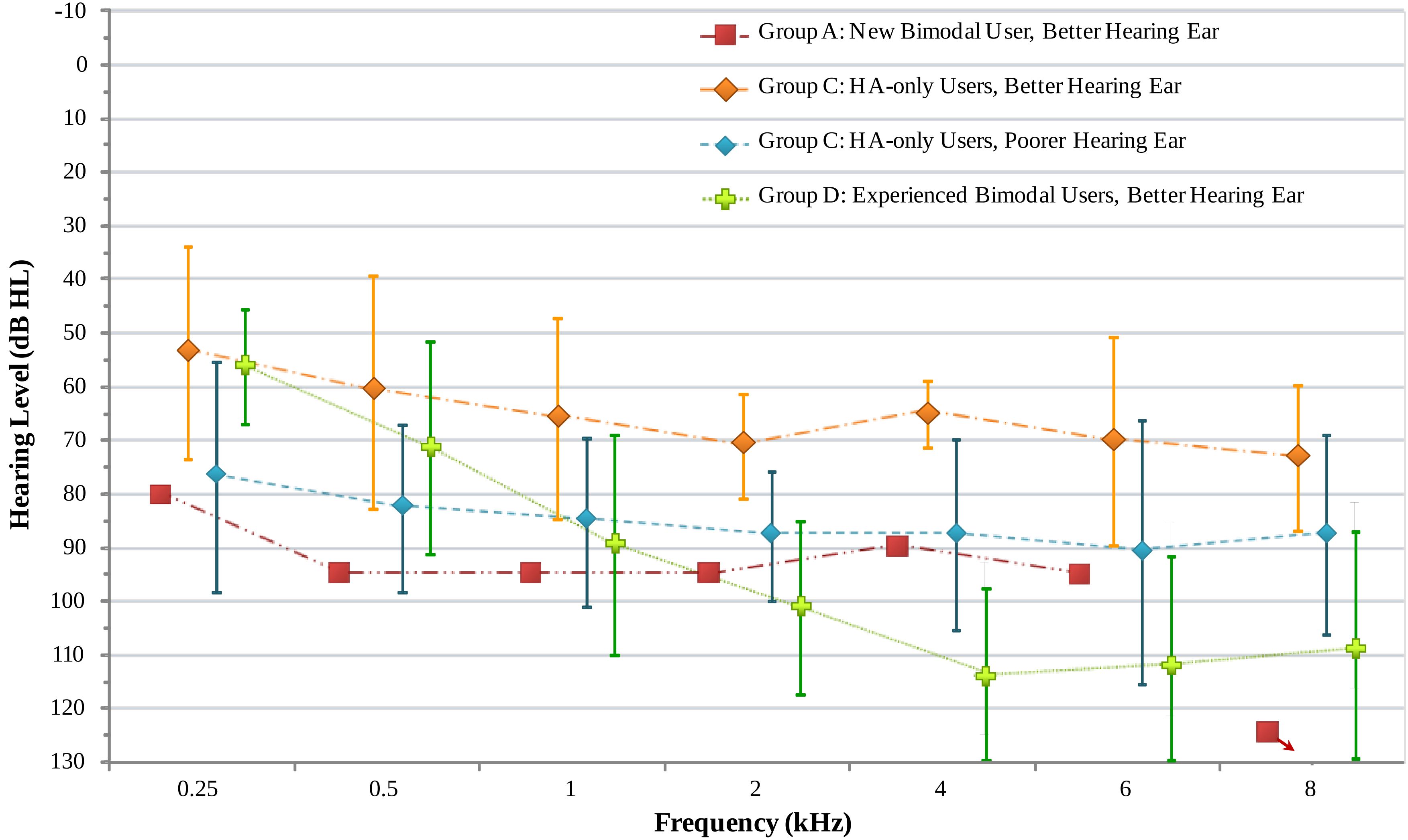

***Figure 5.1*: Summary of unaided hearing thresholds for hearing-impaired groups.**

The CI-only group had no measurable unaided hearing thresholds at all frequencies tested and are not represented in this figure.
Error bars represent ± 1 standard deviation from the mean.
For the HA-only group, only one participant had a threshold that reached the limits of the audiometer (95 dBHL at 8 kHz).
For the eBM group, non-responses were given a value of 130 dBHL.

ID	Gender	Age	MEL	PTA (0.5, 1, 2 kHz; dB HL)	
				Left Ear	Right Ear
E001	F	6.2	2	10.0	10.0
E002	F	11.7	3	10.0	10.0
E003	F	13.5	2	10.0	10.0
E004	F	9.4	2	10.0	10.0
E005	F	5.8	1	13.3	13.3
E006	F	15.4	1	10.0	10.0
E007	M	14.9	1	10.0	10.0
E008	F	13.5	3	11.7	10.0
E009	M	11.0	2	10.0	10.0
E010	M	11.4	2	10.0	10.0
E011	M	8.7	1	18.3	18.3
E012	F	8.4	2	10.0	10.0
E013	F	9.9	3	10.0	11.7
E014	F	15.8	3	10.0	10.0
E015	F	13.2	2	10.0	10.0

Table 5.5: **Participant information for NH group.**
MEL = Musical Experience Level.

ID	Gender	Age (Years)	Implantation Age (Years)	Duration CI Usage (Months)	Ear Implanted	Implant Model	Intracochlear Electrode Array	Speech Processor	Strategy	Stimulation Rate	No. Maxima	No. Active Channels	ADRO
B001	M	14.24	3.16	134.17	R	CI24M	Straight	ESPrit 3G	ACE	900	8	20	N
B002	F	12.73	4.76	95.20	R	CI24M	Straight	ESPrit 3G	ACE	900	8	20	N
B003	M	14.40	3.51	131.63	R	CI24M	Straight	ESPrit 3G	ACE	900	8	20	N
B004	F	12.06	2.37	117.33	R	CI24M	Straight	ESPrit 3G	SPEAK	250	8	20	N
B005	M	13.96	5.09	107.23	R	CI24M	Straight	ESPrit 3G	SPEAK	250	8	20	N
B006	M	11.57	6.48	61.27	L	CI24M	Straight	ESPrit 3G	ACE	900	8	20	N
B007	M	13.35	8.17	78.33	R	CI24M	Contour	ESPrit 3G	ACE	900	8	20	N
B008	M	11.05	8.68	28.20	L	CI24RE	Contour Advance	Freedom	ACE	1200	8	21	Y

Table 5.6: Device details for the CI-only group.

Stimulation rate is per channel, in pulses per second (pps).
ADRO = Adaptive Dynamic Range Optimisation, as described in section 2.3.1.

ID	Gender	Age (Years)	Implantation Age (Years)	Duration CI Usage (Months)	Ear Implanted	Implant Model	Intracochlear Electrode Array	Speech Processor	Strategy	Stimulation Rate	No. Maxima	No. Active Channels	ADRO
A001[ϟ]	F	11.46	9.78	19.80	L	CI24RE	Contour Advance	Freedom	ACE	900	8	22	Y
D001	F	9.41	4.85	54.63	R	CI24R	Straight	Freedom	ACE	900	10	22	Y
D002	M	6.90	4.28	31.53	L	CI24RE	Straight	Freedom	ACE	900	10	22	Y
D003	M	6.38	5.52	12.06	L	CI24RE	Straight	Freedom	ACE	900	10	22	Y
D004	F	8.48	2.62	70.47	L	CI24R	Straight	Freedom	ACE	900	10	22	Y
D006	F	7.44	4.06	85.67	R	CI24M	Straight	Freedom	ACE	900	10	22	N
D007	F	11.10	4.25	86.37	R	CI24M	Straight	Freedom	ACE	900	12	21	Y
D008	M	11.40	5.00	28.67	R	CI24RE	Straight	Freedom	ACE	900	10	22	Y
D009	M	12.86	11.68	13.80	L	CI24RE	Straight	Freedom	ACE	900	8	22	Y

Table 5.7: Cochlear Implant device details for the nBM and eBM groups.

[ϟ]New bimodal user. The stimulation rate is per channel, in pulses per second (pps).ADRO = Adaptive Dynamic Range Optimisation, (see section 2.3.1). Participant D005 was withdrawn from the study prior to testing, so their details are not reported here.

ID	Gender	Age (Years)	Current Aids Fitted	Manufacturer	Model	Prescription Formula	Microphone Setting	PTA BE (0.5, 1, 2 kHz; dB HL)
A001[♮]	F	11.46	June 2008	Phonak	Naida III UP	NAL-NL1	Fixed Omnidirectional	95.0
D001	F	9.41	Oct 2005	Siemens	Prisma 2 D SP	NAL-NL1	Fixed Directional	71.7
D002	M	6.90	May 2008	Siemens	Cielo 2 P	DSL I/O	Fixed Omnidirectional	76.7
D003	M	6.38	Apr 2008	Siemens	Cielo 2 D SP	DSL I/O	Fixed Omnidirectional	101.7
D004	F	8.48	Oct 2007	Siemens	Prisma 2 D SP	NAL-NL1	Fixed Directional	96.7
D006	F	7.44	Mar 2008	Siemens	Prisma 2 D SP	NAL-NL1	Fixed Directional	100.0
D007	F	11.10	Mar 2008	Siemens	Prisma 2 VC+	NAL-NL1	Fixed Directional	91.7
D008	M	11.40	May 2003	Phonak	Powermaxx 411	NAL-NL1	Fixed Omnidirectional	90.0
D009	M	7.41	August 2005	Widex	Senso Diva 9M	NAL-NL1*	Adaptive Directional	70.0

Table 5.8: Hearing aid details for the nBM and eBM groups.

[♮]New bimodal user.
Data relating to participants' initial hearing aid trial (following initial diagnosis) was not available for these users.
'BE' = Better Ear defined as the ear with residual hearing function. *Technically a proprietary strategy closer to NAL-NL2.

ID	Gender	Age (Years)	Duration HA Usage (Months)	Current HAs Fitted	Device Manufacturer	Model	Prescription Formula	Microphone	PTA (0.5, 1, 2 kHz; dB HL) BE	WE
C001	M	13.12	135.10	12/2006	Phonak	Novoforte E4 (L, R)	NAL-NL1	Fixed Omnidirectional	70.0	83.3
C003	F	9.66	127.37	12/2004	Widex	Senso Diva 19* (L, R)	NAL-NL1	Adaptive Directional	83.3	86.7
C004	M	15.02	80.40	04/2008	Widex	Akia AK-19* (L), Akia AK-9* (R)	NAL-NL1	Adaptive Directional	55.0	108.3
C005	M	11.83	90.37	01/2006	Phonak	Powermaxx 411 (L, R)	NAL-NL1	Adaptive Directional	78.3	90.0
C006	F	9.84	99.60	05/2005	Widex	Senso Diva 19* (L, R)	NAL-NL1	Adaptive Directional	40.0	70.0
C007	F	11.51	102.13	11/2005	Widex	Senso Diva 19* (L, R)	NAL-NL1	Adaptive Directional	68.3	71.7

Table 5.9: **Device details for HA-only group.**

'BE' = Better Ear and 'WE' = Worse Ear as determined by a four-frequency (0.5, 1, 2 & 4 kHz) PTA.
All Widex devices used proprietary prescription formulae and speech enhancement technology. In this case all devices used a formula that was based on NAL-NL1, but closer to the as yet unreleased NAL-NL2. There have been no published comparisons of the Widex and NAL formulae to independently verify these claims.

5.3 Materials

5.3.1 Questionnaire

A 42-item Parental Perceptions of Listening Device Performance Questionnaire (PPLDPQ) was used to assess parental perceptions of their child's performance in five categories: device usage (7 questions); performance in quiet (9 questions); performance in background noise (10 questions); environmental awareness (9 questions); and music and fine structure (9 questions). The first four categories were based on a questionnaire developed by Ching and colleagues (2004). The fifth category was added specifically for this study to examine parental perceptions of their child's performance on tasks that benefit from a perception of temporal fine structure information. Parents were asked to rank a series of statements using a five-point scale according to how strongly they agreed/disagreed with the statements. Questions were worded in both the positive and the negative. Example questions from each category are illustrated in *Figure 5.2*, and the entire questionnaire is available in Appendix

Figure 5.2: **Example Questions from the Parental Perceptions of Listening Device Performance Questionnaire**

Questions 1, 2, 3, 4 and 5 are from the device usage, music and fine structure, environmental awareness, speech in quiet, and speech in noise categories respectively.

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
Thinking about your child's current situation, please rank the following statements					
1. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
2. My child enjoys listening to music	☐	☐	☐	☐	☐
3. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
Thinking about your child's current situation, please rank the following statements for ***quiet situations***					
4. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
Thinking about your child's current situation, please rank the following statements for ***noisy situations***					
5. My child is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐

XI. For the device usage subdomain, the parents of children in the CI-only and HA-only groups were questioned regarding the use of their primary listening devices, while the eBM group was questioned regarding their HA only.

5.3.2 Speech Recognition Tests

Monosyllabic word and sentence recognition tests were conducted. Sentence recognition is an easier task than word recognition as sentences have greater redundancy, due to the inclusion of grammatical and contextual cues (Tyler & Lowder, 1992). The results of sentence-based perceptual tasks better represent the performance of patients in real listening situations. However as most CI users have excellent open-set speech perception in quiet, these tests can be prone to ceiling effects, many CI users scoring near 100% correct. In view of this, participants were also assessed using tests of word recognition.

Open-set tests of sentence recognition were used because they more closely resemble normal conversation compared with closed-set tests (Blamey et al., 1996). Testing with background noise at a signal-to-noise ratio (SNR) of 10 dB was also undertaken to assess performance in more challenging listening environments. The CNC words and HINT sentence lists were used in the present study. These were the same speech tests used by the SCIP for pediatric assessments and were spoken by a female talker with a New Zealand accent.

5.3.2.1 HINT Sentences

The Hearing in Noise Test (HINT) is comprised of 25 sentence lists, each list containing ten sentences. Originally developed by Nilsson, Soli & Sullivan (1994), the HINT sentence lists use material from the Bamford-Kowal-Bench (BKB) sentence lists, originally developed for use with children in the United Kingdom (Bench, Kowal, & Bamford, 1979). For the HINT, sentences were equated in terms of length, difficulty, tense and phonemic content. As per SCIP protocol, sentences were scored according to the % of keyword correctly repeated, repeated to give a total % correct score.

5.3.2.2 CNC Word Lists

The Consonant-Nucleus-Consonant (CNC) word lists were developed by Lehiste and Peterson (1959). Words used in this test were derived from the word lists developed by Thorndike and Lorge (1944). Thorndike and Lorge's lists were roughly phonemically balanced and approximately equivalent in difficulty. Each CNC word is monosyllabic with an initial consonant, vowel, and final consonant. Each of these components are phonetically balanced within a list, (i.e. they appear with the same frequency of occurrence within each list). The finalised CNC words test consists of 10 lists of 50 words each.

5.3.3 Pitch Ranking Task

Development of this task is described in detail in Sucher & McDermott (2007). The stimuli used in this test are recordings of the vowel */a/* sung by a trained male or female singer. The recordings were combined into pitch pairs, consisting of two different notes of the same vowel, sung by the same singer, at a designated interval size. Three interval sizes were used in this test: full octave (12 semitones), ½ octave (6 semitones) and ¼ octave (3 semitones). These interval sizes constituted separate subtests and were presented order of decreasing interval size (1, ½ then ¼ octave). There were a total of eight waveform recordings for each pitch pair – four where the first note was higher than the second note (i.e. descending), and four in the reverse order (i.e. ascending). A wide range of F0s were incorporated into the test (see Figure 5.3 and Table 5.10). Participants were required to indicate whether a vowel pair increased in pitch (1 → 2) or decreased in pitch (3 → 4) (see Figure 5.3).

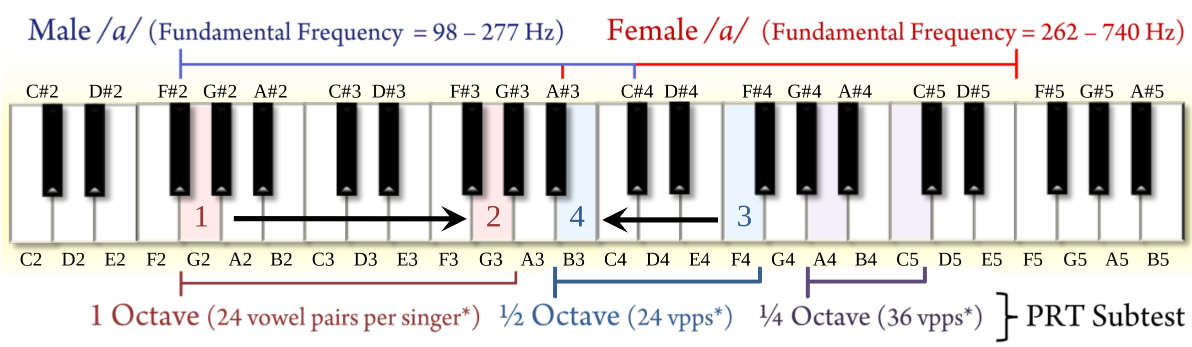

***Figure 5.3*: Diagram summarising the main features of the Pitch Ranking Task.**

*VPPS: Vowel pairs per singer.

Subtest	Fundamental frequency of stimuli used for each interval
1 Octave	
Female	C4-C5 (262-532 Hz); D#4-D#5 (311-622 Hz); F#4-F#5 (370-740 Hz)
Male	G2-G3 (98-196 Hz); A#2-A#3 (117-233 Hz); C#3-C#4 (139-277 Hz)
½ Octave	
Female	C4-F#4 (262-370 Hz); F#4-C5 (370-523 Hz); C5-F#5 (523-740Hz)
Male	G2-C#3 (98-139 Hz); C#3-G3 (139-196 Hz); G3-C#4 (196-277 Hz)
¼ Octave	
Female	C4-D#4 (262-311 Hz); D#4-F#4 (311-370 Hz) G#3-C4 (196-277 Hz); A4-C5 (440-523 Hz)
Male	C#3-E3 (139-165 Hz); E3-G3 (165-196 Hz); G3-A#3 (196-233 Hz); A#3-C#4 (233-277 Hz)

Table 5.10: Fundamental frequencies of stimuli used in the Pitch Ranking Task.

5.4 Equipment

Stimuli for each test were presented via a computer connected to a Creative Soundblaster Extigy external soundcard. MACArena, a flexible computer based speech testing platform (Lai & Dillier, 2002), was used to randomise Pitch Ranking Task (PRT) stimulus presentation and record responses for further analysis.

Testing took place in sound-treated rooms at either the University of Canterbury or the SCIC. At the University of Canterbury sound was output via a Crown D-75A 2-channel amplifier connected to a pair of Bowers & Wilkins DM303 loudspeakers. At the SCIC the amplifier was a Technics SU-7300 amplifier connected to a pair of unbranded loudspeakers.

Pre-test tympanometry was performed using a GSI Tympstar middle ear analyser (UoC) or an Interacoustics MT10 handheld tympanometer (SCIC). Puretone Audiometry was conducted using a Grason-Stadler GS1 clinical audiometer with appropriately calibrated insert 3A earphones or TDH-39 supra-aural headphones.

Group A hearing aid adjustments were made using the appropriate hearing aid manufacturer software and validated using a Audioscan Verifit VF-1 real ear analyser.

5.5 Procedures

All testing was conducted in sound treated audiology test rooms. Ambient noise levels were measured using a sound level meter to ensure that they were below an L_{eq} of 39 dB(A) in accordance with the American National Standards Institute (ANSI) standards (Frank, 2000) prior to each testing session. Stimuli for all tests were calibrated at the position of the listener's ear with a margin of error of ± 1 dB. Standardised written and/or verbal instructions were provided for all tasks and all participant groups.

5.5.1 Testing Schedule

A summary of each groups' testing schedule is provided in Figure 5.4.

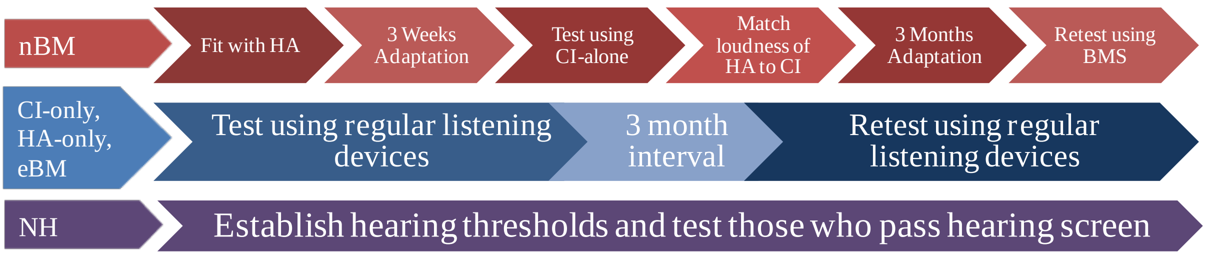

Figure 5.4: Appointment summary for participants from each group.

Group A: new users of Bimodal Stimulation (nBM)

Participants in group A attended four appointments (see *Figure 5.4*). The first two appointments took place with the child's audiologist and involved the reassessment of hearing thresholds, and HA counselling and fitting. Aids were fitted using the NAL-NL1 prescription with wide dynamic range compression which has been used effectively in Bimodal Stimulation (BMS) fittings in previous studies (Lai & Dillier, 2002). A schedule of HA use was negotiated between the participant, their parent/caregiver(s) and their audiologist with the aim of using the HA (in conjunction with their CI) for at least 8 hours a day within three weeks of the initial fitting. A questionnaire assessing parental perceptions of the child's performance using their CI was filled in by the child's parent/caregiver(s) and returned at the end of the appointment.

The third and fourth appointments took place at the UoC. The third appointment took place three weeks after the second, to ensure each participant had time to adjust to their new HA. Subjects were assessed on tasks of speech recognition and pitch perception (see section 5.5.2) using their CI-alone. The loudness and frequency response of their HA was then optimised with their CI according to protocols developed by Ching et al. (2004). Participants were then asked to wear the optimised HA with their CI for at least 8 hours a day until the next testing session.

The fourth appointment took place three months after the third and involved reassessment using the same tests of speech recognition and pitch perception using BMS, and the completion of a questionnaire assessing parental perceptions of the child’s performance using BMS. At the conclusion of testing there was a general discussion of the child’s results comparing scores in the CI-only condition versus the BMS condition. Where appropriate, participants and their parent/caregiver(s) were encouraged to continue HA use, although they had the option of returning the hearing aid if they wished.

Groups B, C & D: CI-only, HA-only and Experienced Bimodal (eBM) Users

Groups B, C and D attended two testing sessions, three months apart (see *Figure 5.4*). Participants were assessed using the same tests of speech and pitch perception (see section 5.5.2) as group A, using their normal listening devices. Puretone audiometry was also conducted for group B to confirm the absence of residual hearing in their non-implanted ear. The parent/caregivers of children in all groups completed the PPLDP. No adjustments to the child’s hearing devices were made during either appointment. Checks were performed to ensure the same listening programs and settings were used at each appointment. Appointments for groups B and C were held at the UoC clinic, while those for group D were held at the SCIC.

Group E: Normal-Hearing Listeners

Due to time constraints, participants in group E were only tested once. Their hearing was screened to ensure that thresholds were within normal limits. Participants were then assessed using the PRT and HINT sentence tasks, with the session taking approximately 90 minutes. The primary focus of testing group E participants was to obtain a NH baseline for the PRT.

5.5.2 Session Protocols

Each session began with a check of middle ear pressure and compliance using standard tympanometric procedure to check for middle ear dysfunction that might impact on the results obtained. Participants were then assessed using the CNC word and HINT sentence lists, and a Pitch Ranking Task (PRT). The order of these tests was pseudo-randomised in order to eliminate any effects of test order on performance. The lists used for each speech test, and each HINT listening condition, were also pseudo-randomised. The PRT proceeded in order of decreasing interval size, with singer gender being pseudo-randomised. Pairs of sung vowels within each PRT subtest were randomised by the MACArena software.

CNC word list material was presented over a loudspeaker positioned 1.0m from, and 0° azimuth relative to the participant, at a level of 65 dBSPL. The participant was instructed to look directly toward the loudspeaker and to repeat what they heard, guessing if unsure. One CNC word list was used and responses were totalled to give two scores: percentage words correct and percentage phonemes correct.

HINT sentence material was presented in four listening conditions: one in quiet (S0), and three with the concurrent presentation of competing four-talker babble (S0N0, S0NCI, S0NHA) as detailed below. In all conditions, HINT sentence material was presented over a loudspeaker at a fixed distance with respect to the subject at a level of 65 dBSPL at the listeners' ear. For conditions involving background noise, four-talker babble was presented at a SNR of 10 dB. Two HINT sentence lists were presented for each of the four listening conditions. The participant was instructed to repeat what was heard and guess if unsure.

Performance was evaluated on the total percentage of key words repeated correctly for each listening condition.

In the S0 condition, HINT sentences were presented in quiet over a loudspeaker positioned at 0° azimuth (see *Figure 5.5*). This arrangement allows for the isolation of the benefits of binaural redundancy in quiet through minimisation of head diffraction effects (Ching et al., 2001; see Appendix I for details). For group A, scores in this condition were used as a baseline measure of performance in order to check for binaural interference, indicated by lower scores when using BMS than when using a CI-only (Ching et al., 2006; Morera et al., 2005).

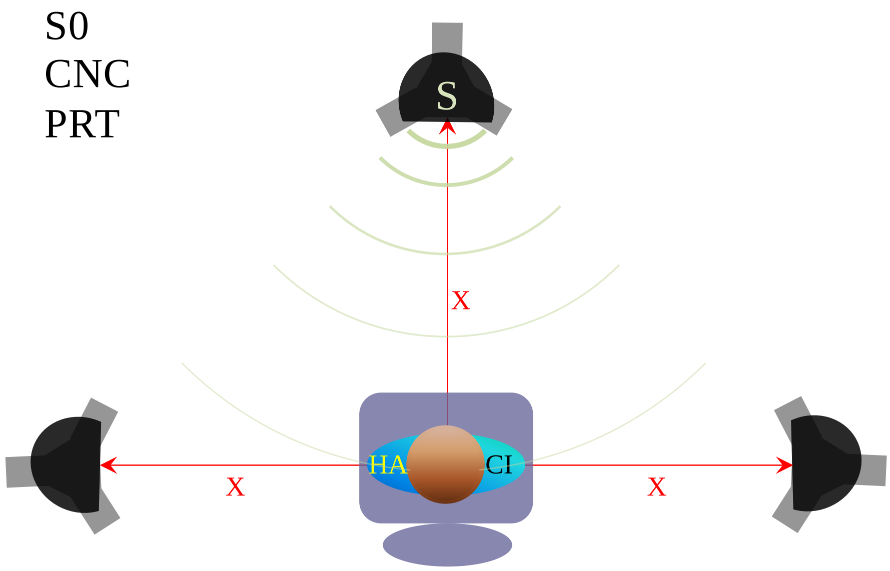

Figure 5.5**:** **Speaker setup for CNC words, HINT sentences in quiet and Pitch Ranking Task.**
'X': the distance between the participant and the loudspeaker was 1m for sessions conducted at the UoC.
At the SCIC 'X' was 0.75m for all HINT listening conditions and 1.0m for the PRT and CNC word lists.

For the S0N0 condition, HINT sentence material was presented concurrently with four-talker babble from a single loudspeaker positioned at 0° azimuth with respect to the participant (see *Figure 5.6*). This speaker configuration was chosen as it allows for the isolation of the benefits of 'binaural summation' in noise through minimisation of the benefits of head diffraction effects (Ching, 2005).

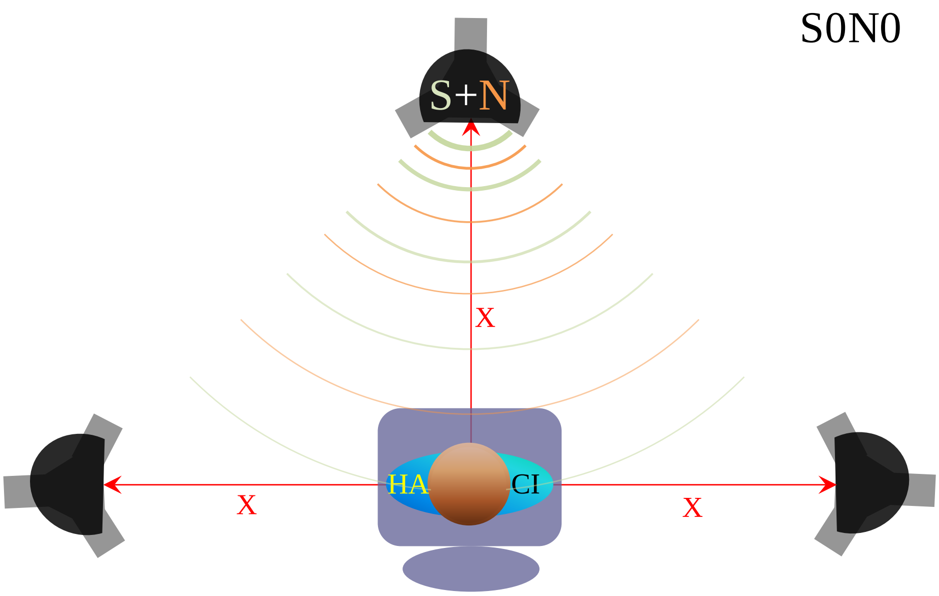

Figure 5.6: **Speaker setup for the HINT sentence in noise S0N0 listening condition.**
'S' and 'N' designate the presentation of signal and noise (4 talker-babble) respectively.
'X': the distance between the participant and the loudspeaker was 1.0m for sessions conducted at the UoC and 0.75m at the SCIC.

For the S0NCI and S0NHA conditions, HINT sentences and four-talker babble were presented simultaneously from spatially separated loudspeakers positioned at 0° and 90° degrees azimuth respectively (see *Figure 5.7*). For the S0NCI condition, noise was presented via the loudspeaker closest to the participant's CI (groups A, B and D), better hearing ear[10] (group C), or right ear (group D). For the S0NHA condition, noise was presented from the loudspeaker closest to the participant's non-implanted ear (groups A, B and D), poorer hearing ear (group C), or left ear (group E). These speaker configurations were chosen as they maximise head diffraction effects, allowing for the isolation of the head shadow effect (Ching et al., 2006).

[10] For the purpose of statistical analysis the better hearing ear of participants in group C was defined as: the ear with the lowest 4-frequency (0.25, 0.5, and 1 kHz) average unaided hearing thresholds, as determined by puretone audiometry.

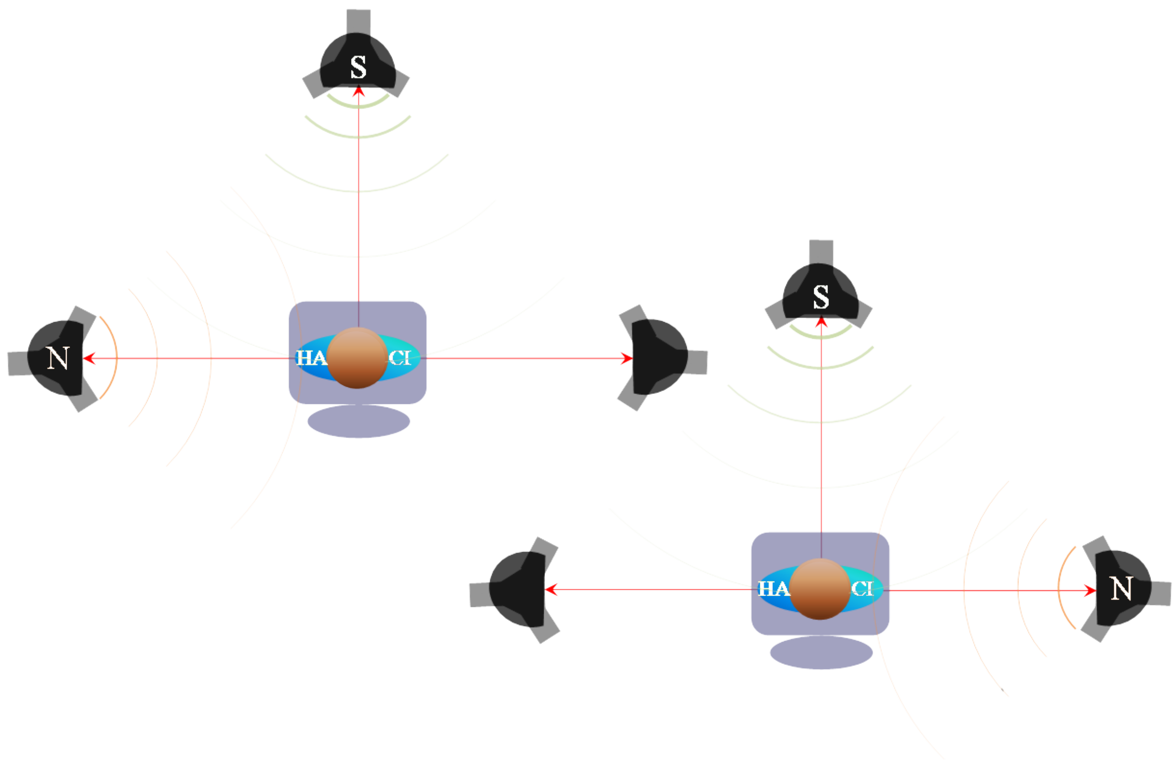

Figure 5.7: **Speaker setup for the HINT sentence in noise S0NCI and S0NHA listening conditions.**
'S' and 'N' designate the presentation of signal and noise (4 talker-babble) respectively.
'X': the distance between the participant and the loudspeaker was 1.0m for sessions conducted at the UoC and 0.75m at the SCIC.

Participants were then assessed using the PRT. Stimuli were presented at 65 dBSPL from a loudspeaker was positioned at 1.0m from and 0° azimuth relative to the participant (see *Figure 5.5*). Participants were instructed to listen to each pair of vowels and decide whether they were increasing or decreasing in pitch. The concepts of higher and lower were explained using practice test stimuli in conjunction with the pictures in Appendix II, a ladder representing increasing pitch, and a slide representing decreasing pitch. Participants were trained using stimuli from the 1 octave subtest and assessment commenced once they had obtained either 8 consecutive correct responses, or 9/12 correct responses, whichever came first. During training, repetition of stimuli was used where necessary and feedback regarding the accuracy of responses was provided.

Participants in the present study were required to respond using a motor response (i.e. raise/lower their arm from a neutral position), followed by verbal confirmation of their response, i.e. "up" (ascending pitch) or "down" (descending pitch). Pilot testing showed that the addition of the motor task seemed to reduce participant fatigue and helped to keep the children more attentive. This is supported by the findings of Andrews & Madeira (1977) who reported that children between 6 and 8 years of age were unable to accurately rank pitch using a verbal response, but were able to do so when using a motor response. They hypothesised that use of a motor response reduced the cognitive burden of the task. For younger children, the verbal response was replaced with a picture-pointing task, in which the child pointed to a picture of some stairs (ascending pitch), or a picture of a slide/chute (descending pitch; see Appendix II). No feedback was provided regarding the accuracy of participants' responses, which were recorded in the MACArena software for further analysis. Participants' did not progress onto a smaller interval size when they: (1) scored < 60% correct for a particular interval size; (2) their motor responses were inconsistent or unreliable despite training or instruction, and; (3) the participant admitted that they were guessing.

6 Results

6.1 Data analysis

Data analysis was performed using SPSS Statistics versions 15.0 and 17.0 and StatXact version 6.0. Where applicable, two-tailed statistical tests were used with a significance criterion of $p \leq 0.05$. Bonferroni corrections were used when interpreting Analysis of Variance (ANOVA) results, except when Mauchly's test for the equality of variances was significant, in which case Tamhane T2 corrections were used; or when Mauchly's test of sphericity was significant, in which case Dunett T3 corrections were used. For correlations, the non-parametric Spearman's rho was used.

It should be noted that the number of participants that completed each test or subtest varied. Some of the younger children were unable to concentrate for the entire testing session, even after several breaks. In these circumstances it was more prudent to ensure the child had a positive testing experience, and attempts were made to obtain complete results at a follow-up session where possible. Accordingly, the degrees of freedom (*d.f.*) and number of participants (n) for each subtest and listening condition are reported. As only one nBM user took part in the study, their results were not included in the following statistical analyses and have instead been considered as a separate case study in section 6.7.

6.2 Participant Demographics

A one-way ANOVA conducted to compare the mean chronological age of each group revealed significant between-group differences ($F(3, 33) = 3.124$, $p = 0.039$). Post-hoc analysis using Bonferroni corrections revealed that the Experienced Bimodal (eBM) group ($M = 9.24$ years, $SD = 2.35$) was significantly younger than the CI-only group ($M = 12.92$ years, $SD = 1.27$; $p = 0.036$). There was no significant difference between the age of the HA-only ($M = 11.8$ years) and eBM groups.

A one-way ANOVA conducted to compare the mean age at diagnosis of hearing loss for the hearing impaired groups revealed significant between-group differences ($F(2, 19) = 9.22$, $p = 0.002$). Post-hoc analysis using Bonferroni corrections revealed that the mean age of diagnosis was significantly higher for the HA-only group ($M = 41.17$ months, $SD = 16.61$) than both the eBM ($M = 11.75$ months, $SD = 8.26$, $p = 0.001$) and CI-only groups ($M = 20.25$ months, $SD = 13.56$, $p = 0.022$). There was no significant difference in the mean age of diagnosis between the CI-only and eBM groups ($p = 0.867$) .

An independent samples t-test was conducted to compare the mean age at implantation of the CI-only and eBM groups. There was no significant difference in the mean age at implantation between the CI-only ($M = 5.78$, $SD = 2.99$) and eBM groups ($M = 5.40$, $SD = 2.76$). An independent samples t-test was also conducted to compare the mean duration of device usage for the CI-only and eBM groups. At the time of testing, the CI-only group had used their CI for a significantly longer duration ($M = 7.26$ years; $SD = 3.51$) than the eBM group ($M = 3.95$ years; $SD = 2.50$; $p = 0.047$). An independent samples t-test found no significant difference between the better hearing ear mean low-frequency puretone average (PTA; 0.25, 0.5, 1.0 kHz) of the HA-only and eBM groups ($t = 1.536$, $d.f. = 12$, $p = 0.151$). A Kruskal-Wallis test was conducted to compare the Music Experience Level (MEL) of all four subject groups. No significant between-group differences for MEL were found.

6.3 Speech Recognition Tests

Technical difficulties beyond the researchers control severely disrupted session one speech testing for the eBM group. As a result the CNC word list and HINT sentence scores from this session were excluded from further analyses to ensure that all comparisons were made between data collected under equivalent testing conditions. Participants in the NH group were not assessed using the CNC word lists.

6.3.1 CNC Word Lists

6.3.1.1 Learning Effects

Individual paired-samples t-tests were conducted to assess whether there were any learning effects for the CI-only and HA-only groups. No significant between-session differences in score were found for the CNC word or phonemes scores for either group, hence the data from the two sessions was combined for each group for further analysis (see Table 6.1).

		% CNC Words Correct		% CNC Phonemes Correct	
	n	*M*	*SD*	*M*	*SD*
CI-only	15	71.87	14.79	87.33	7.95
HA-only	13	65.39	11.54	82.34	7.13
eBM	9	76.45	14.79	89.45	6.24

Table 6.1 Group means for the CNC Word Lists (sessions combined).

6.3.1.2 Between-Group Differences

A one-way ANOVA was performed to compare the CI-only, HA-only and eBM groups' CNC words and phonemes correct scores. There were no significant between-group differences in performance for CNC words ($F(2, 31) = 1.519$, $p = 0.235$), or CNC phonemes ($F(2, 31) = 2.367$, $p = 0.110$).

In the current study, all but one member of the CI-only group scored ≥ 50% on the CNC word lists, similar to participants in Dorman et al. (2008), who reported a significant difference in the proportion of 'high-scoring' CI-only and adult eBM users on a range of speech perception tasks (see section 3.3 for details). It was thought worthwhile to investigate whether a similar trend was evident in the present study. *Figure 6.1* summarises the distribution of mean % CNC word-correct scores for each participant according to subject group. Six of the eight eBM users (80%) in our study scored ≥ 80% correct on the CNC words, compared to only two of the eight CI-only users (25%) and one of six HA-only users

(16.7%). The results of separate Barnard's exact tests[11] revealed that the proportion of eBM users who scored ≥ 80% correct was significantly greater than the proportion of CI-only users (p = 0.038) and HA-only users (p = 0.022) who scored ≥ 80% correct. There was no significant difference in the proportion of CI-only and HA-only users who scored ≥ 80% correct.

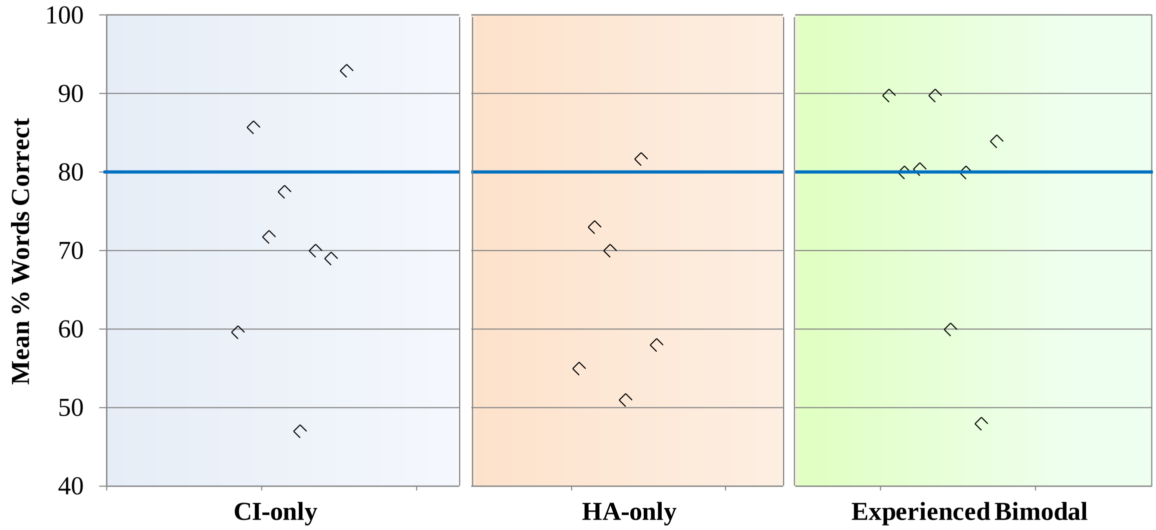

Figure 6.1: **Distribution of mean CNC-word correct scores for participants in the CI-only, HA-only and eBM groups.**

6.3.2 HINT Sentences

6.3.2.1 Learning Effects

Individual paired-samples t-tests were conducted for the CI-only and HA-only groups in order to assess for the presence of a learning effect for each of the four HINT listening conditions: speech in quiet (S0); speech with spatially co-incident noise (S0N0); and speech with noise originating from a speaker at 90° azimuth on the side of the participants CI/ better hearing ear (S0NCI) or their HA/ worse hearing ear (S0NHA; 10 dB SNR; see *Figure 5.7*). There were no significant between-session differences in score for any of the four HINT sentence listening conditions for either the CI-only or the HA-only groups.

[11] Barnard's exact test was chosen because it offers a more powerful analysis of 2 x 2 contingency tables than Fisher's exact test, and is more accurate for very small sample sizes (Mehta & Hilton, 1993).

Accordingly, scores from the two sessions for each group were combined for further analysis. A summary of results is displayed in Table 6.2.

Listening Condition	S0 (%Correct)		S0N0 (%Correct)		S0NCI (%Correct)		S0NHA (%Correct)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
CI-only								
Session 1	93.66	12.06	90.35	11.25	82.65	16.88	88.75	16.88
Session 2	92.18	11.85	85.56	16.23	87.40	15.28	91.66	13.38
Combined	92.97	11.56	88.12	13.50	84.87	15.77	90.12	11.05
HA-only								
Session 1	97.28	2.91	93.30	5.30	88.88	8.07	91.20	8.90
Session 2	93.68	5.87	93.49	6.75	94.03	3.57	93.51	8.89
Combined	95.64	4.64	93.39	5.68	91.22	6.70	92.25	8.52
eBM								
Session 2	95.74	4.21	91.96	5.69	92.00	5.50	91.76	7.57
NH								
Session 1	99.81	0.40	99.61	0.79	99.63	0.68	99.62	0.70

Table 6.2 Summary of mean HINT sentence scores.

As mentioned previously, session 1 scores for the eBM group were excluded from analysis due to technical difficulties beyond the researchers' control.
The NH group was only tested once.

6.3.2.2 Between-Group and Between-Listening Condition Differences

A two-way repeated-measures (RM) ANOVA was performed to assess for differences between the participant groups for the four listening conditions. Significant effects were found for: the between-subject factor of group ($F(3, 43) = 4.960$, $p = 0.005$); and the within-subject factor of listening condition ($F(3, 41) = 8.196$, $p < 0.001$); with a significant interaction between these factors ($F(9, 129) = 2.076$, $p = 0.036$).

In view of the significant interaction, separate one-way ANOVAs were conducted for each group and listening condition. One-way ANOVAs for each listening condition showed significant differences between group mean scores for all three sentence in noise conditions: S0N0 ($F(3, 45) = 4.91$, $p = 0.005$); S0NCI ($F(3, 44) = 5.76$, $p = 0.002$); S0NHA ($F(3, 44) = 4.17$, $p = 0.001$). There were no significant between-group differences for the S0 condition although this result approached significance ($F(3, 45) = 2.418$, $p = 0.079$). Post-hoc analysis using Dunnett T3 corrections revealed that:

- In the S0N0 condition, the NH group scored significantly higher than the CI-only ($p = 0.029$), HA-only ($p = 0.025$) and the eBM groups ($p = 0.028$);
- In the S0NCI condition, the NH group scored significantly higher than the CI-only ($p = 0.016$) and HA-only ($p = 0.010$) groups, but not the eBM group;
- In the S0NHA condition, the NH group scored significantly higher than the CI-only group ($p = 0.036$), but not the HA-only or eBM groups.
- There were no significant differences between the mean scores of the CI-only, HA-only and EAS groups (see *Figure 6.2*).

Due to the lack of significant differences between the CI-only and eBM groups for all listening conditions, an estimation of the size of the effects of ‘binaural redundancy’ and the ‘head shadow effect’ was not conducted.

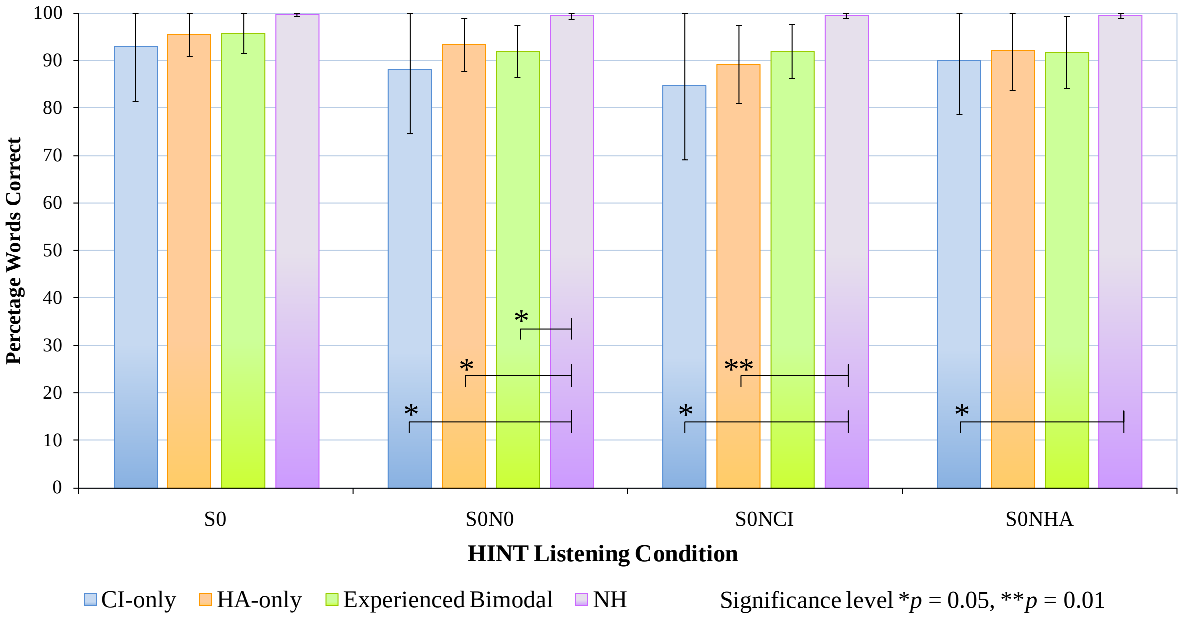

Figure 6.2: **Summary of between-group differences for the HINT sentence lists.** Error bars represent ± 1 standard deviation from the mean.

Repeated measures one-way ANOVAs were also performed for each individual group in order to determine the effect of listening condition on HINT sentence score. There were no significant between-condition differences for the CI-only (F(3, 56) = 1.00, p = 0.40); HA-HA-only (F(3, 68) = 0.730, p = 0.54) eBM (F(3,26) = 0.85, p = 0.48) and NH groups (F(3, 56) = 0.30, p = 0.83) . In summary, listening condition had no significant effect on HINT sentence performance for any participant group (see *Figure 6.3*).

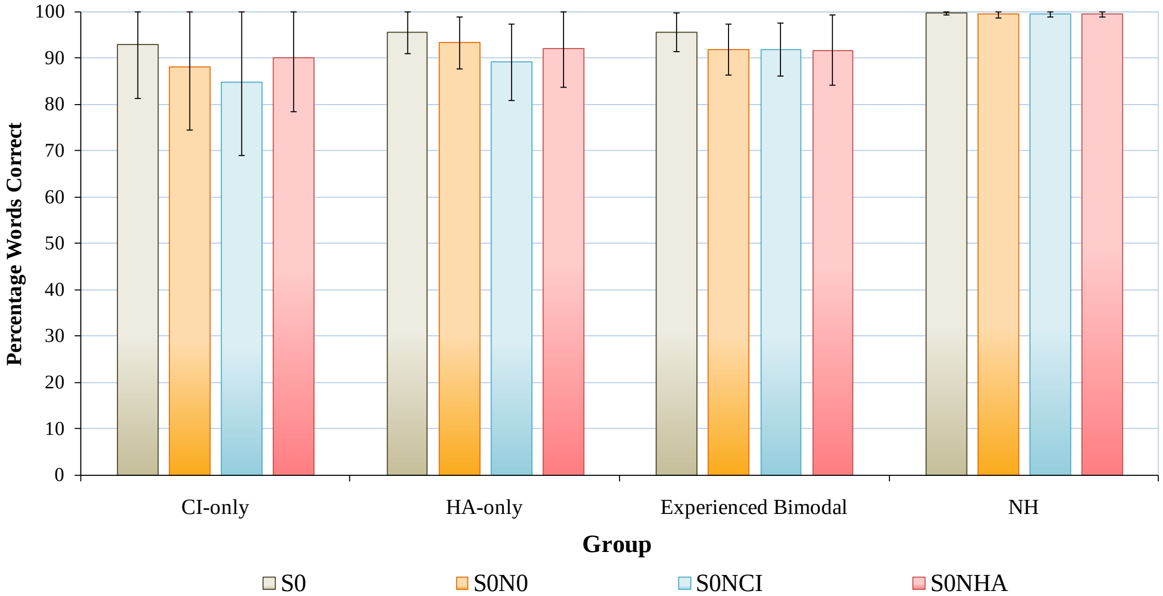

***Figure 6.3*: Summary of within-group comparisons for 4 HINT sentence listening conditions.**

For the HA-only group S0NCI = noise presented to the better ear while S0NHA = noise presented to the poorer ear.
Error bars represent ± 1 standard deviation from the mean.

A comparison of the proportion of high-performing participants in the CI-only and eBM groups was not possible due to ceiling effects as too few participants scored < 85% correct across all listening conditions (see *Figure 6.4*).

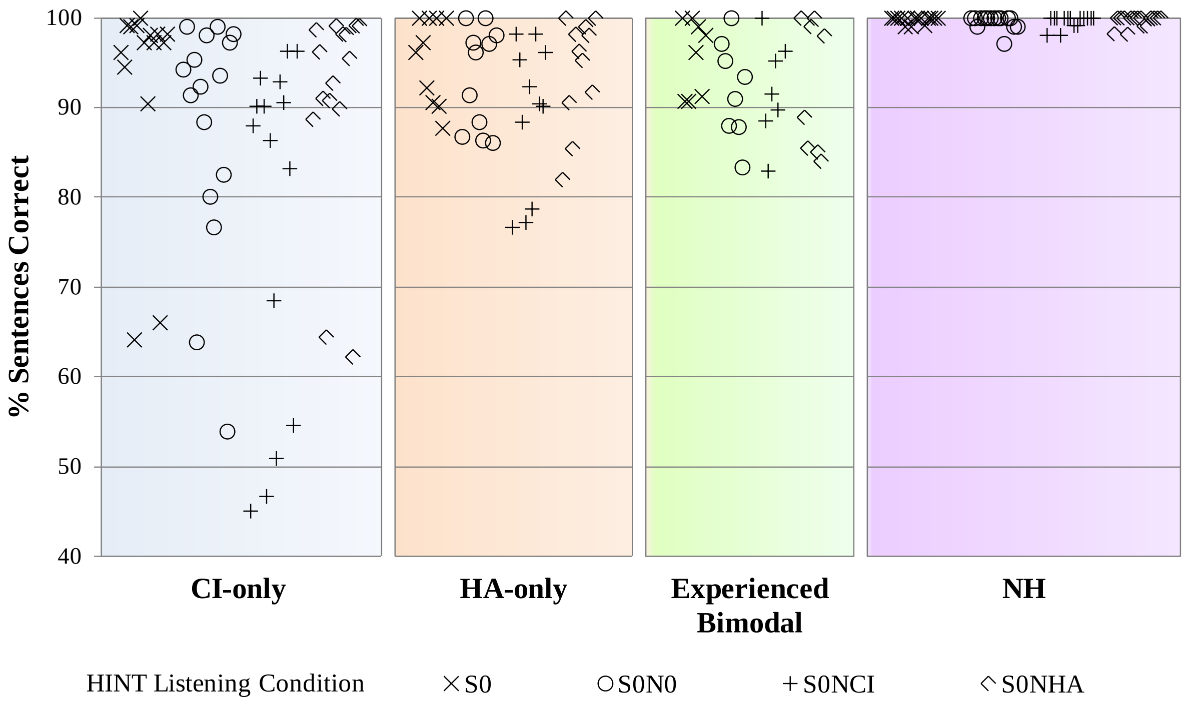

Figure 6.4: **Distribution of HINT sentence scores across all four listening conditions.** Each point represents an individuals' score for a particular testing session.

6.4 Pitch Ranking Task

For the PRT, stimuli were sung vowels, specifically the vowel */a/*, sung by either a male or female singer. The pitch interval between each member of a pair was either a whole (1), ½ or a ¼ quarter octave, each interval size constituting a separate subtest. Participants were required to state whether a given vowel pair ascended or descended in pitch. The number of participants who completed the PRT varied between session and subtest (see Table 6.3). A summary of group mean results is available in Table 6.4. Overall, the NH group scored the highest across all three subtests, followed by the HA-only, CI-only and eBM groups respectively.

Group	*n*	Session 1						Session 2					
		1 Oct.		½ Oct.		¼ Oct.		1 Oct.		½ Oct.		¼ Oct.	
		F	M	F	M	F	M	F	M	F	M	F	M
CI-only	8	6	6	5	5	5	5	7	7	6	6	5	5
HA-only	6	5	5	5	5	5	5	5	5	5	5	4	5
eBM	8	6	6	6	6	6	4	8	8	7	6	6	5
NH	15	15	15	15	15	15	15	N/A	N/A	N/A	N/A	N/A	N/A

Table 6.3: Number of participants who completed each Pitch Ranking Task subtest.

PRT Subtest	1 Octave		½ Octave		¼ Octave	
	M	*SD*	*M*	*SD*	*M*	*SD*
CI-only						
Session 1	80.14	21.60	79.17	10.81	64.84	15.26
Session 2	86.01	13.75	76.04	13.78	70.05	13.94
Combined	83.30	18.59	77.60	12.21	67.45	14.54
HA-only						
Session 1	95.83	5.55	86.67	11.75	74.38	22.81
Session 2	95.00	11.75	90.42	10.59	84.38	15.23
Combined	95.42	8.96	88.54	11.06	79.11	19.74
eBM						
Session 1	73.95	15.08	75.34	18.67	61.26	19.98
Session 2	83.85	14.10	74.68	12.32	64.68	20.31
Combined	79.61	15.10	75.00	15.36	63.99	19.99
NH						
Session 1	96.94	5.35	94.58	8.06	88.79	11.033

Table 6.4: Group mean scores for each of the Pitch Ranking Task subtests.

6.4.1 Learning and Singer-Gender Effects

For each group, Wilcoxin signed-rank tests or Paired-samples t-tests were used to assess for significant learning effects (between-session increases in PRT score) and singer-gender effects (differences between scores for male and female sung stimuli), as detailed below. If a participant obtained ceiling level scores of 100% on a specific subtest at *both* testing sessions their data was removed from the learning effect analyses, as their between-session difference scores of zero would have resulted in an underestimation in the magnitude of any learning effects. The NH group were only assessed using the PRT once, so their data has been excluded from the learning effect analyses and included in the singer-effect analyses only.

Individual paired-samples t-tests for each group and each subtest were conducted to determine whether there was any effect of singer gender. For the CI-only group, there was no effect of singer gender for the 1 (p = 0.400), ½ (p = 0.714) or ¼ octave subtests (p = 0.279). Nor was there any significant effect of singer gender on the scores of the HA-only group on the 1 (p = 0.124), ½ (p = 0.882) or ¼ octave subtests (p = 0.824). There was no significant effect of singer gender for the BMS group for the 1 (p = 0.372), ½ (p = 0.683) or ¼ octave subtests (p = 0.116). Finally, there was no significant effect of singer gender on the NH groups scores on the 1 (p = 0.138), ½ (p = 0.607) or ¼ (p = 0.215) octave subtests. In summary, there was no significant effect of singer gender therefore scores were pooled in further analyses.

The CI-only group showed a significant improvement in scores for the 1 octave subtest (p = 0.028) but not the ½ (p = 0.833) and ¼ octave (p = 0.406) subtests. Scores for the HA-only group improved significantly for the 1 (p = 0.042), ½ (p = 0.027) and ¼ (p = 0.043) octave subtests. The BMS group showed a significant learning effect on the 1 octave subtest (p = 0.025), but not the ½ (p = 0.483) or ¼ octave subtests (p = 0.600). In summary, the HA-only group showed a significant improvement in performance on all three PRT subtests, but the performance of the CI-only and BMS groups improved for the 1 octave subtests only.

6.4.2 Chance Performance

1-sample t-tests were conducted to determine whether groups performed at significantly better than chance levels (a score of 50%) on each PRT subtest. The CI-only group performed at levels that were significantly better than chance on the 1 octave ($t(31) = 2.73$, $p = 0.011$), ½ octave ($t(21)=10.49$, $p < 0.001$), and ¼ octave subtests ($t(19) = 5.06$, $p < 0.001$). Similarly, the HA-only group performed at levels significantly better than chance on the 1 octave subtest ($t(19) = 22.68$, $p < 0.001$), ½ octave ($t(19) = 15.59$, $p < 0.001$), and ¼ octave subtests ($t(18) = 6.43$, $p < 0.001$). The eBM group also performed at levels that were significantly better than chance on the 1 octave ($t(31) = 2.71$, $p < 0.001$), ½ octave ($t(24) = 8.14$, $p < 0.001$) and ¼ octave subtests ($t(18) = 3.050$, $p = 0.007$). In summary, all groups performed at significantly better than chance levels on all PRT subtests.

6.4.3 Between-Group Differences

A two-way RM ANOVA was conducted to investigate whether the between-subject factor of group and/or the within-subject factor of subtest had any significant effect on PRT score. Significant effects were found for subtest ($F(2, 83) = 47.83$, $p < 0.001$) and group ($F(3, 84) = 15.75$, $p <0.001$), with a significant interaction between these factors ($F(5.254, 147.12) = 2.893$, $p = 0.014$).

In view of the significant interaction, separate one-way ANOVAs were conducted for each subtest to determine the effect of group on PRT score. Significant between-group differences were found for the 1 octave ($F(3, 100) = 11.68$, $p < 0.001$), ½ octave ($F(3, 93) = 15.79$, $p < 0.001$), and ¼ octave subtests ($F(3, 84) = 11.51$, $p < 0.001$), scores being higher for the larger interval sizes.

Post-hoc analysis using Dunnett T3 corrections revealed the following (as summarised in *Figure 6.5*). For the 1 octave subtest: the HA-only group scored significantly higher than the CI-only ($p = 0.035$) and eBM groups ($p < 0.001$); and the NH group scored significantly higher than the CI-only ($p = 0.007$) eBM groups ($p < 0.001$). For the ½ octave subtest: the

HA-only group scored significantly higher than the CI-only ($p = 0.026$) and eBM groups ($p = 0.008$), and; the NH group scored significantly higher than the CI-only ($p < 0.001$) and eBM groups ($p < 0.001$). For the ¼ octave subtest, the NH group scored significantly higher than the CI-only ($p < 0.001$) and eBM groups ($p < 0.001$). In summary, the HA-only group scored significantly higher than both the CI-only and eBM groups on the 1 and ½ octave subtests, and the NH group scored significantly higher than both the CI-only and eBM groups on all three subtests (see *Figure 6.5*). There were no significant between-group differences in PRT scores for the CI-only and eBM groups, or the HA-only and NH groups.

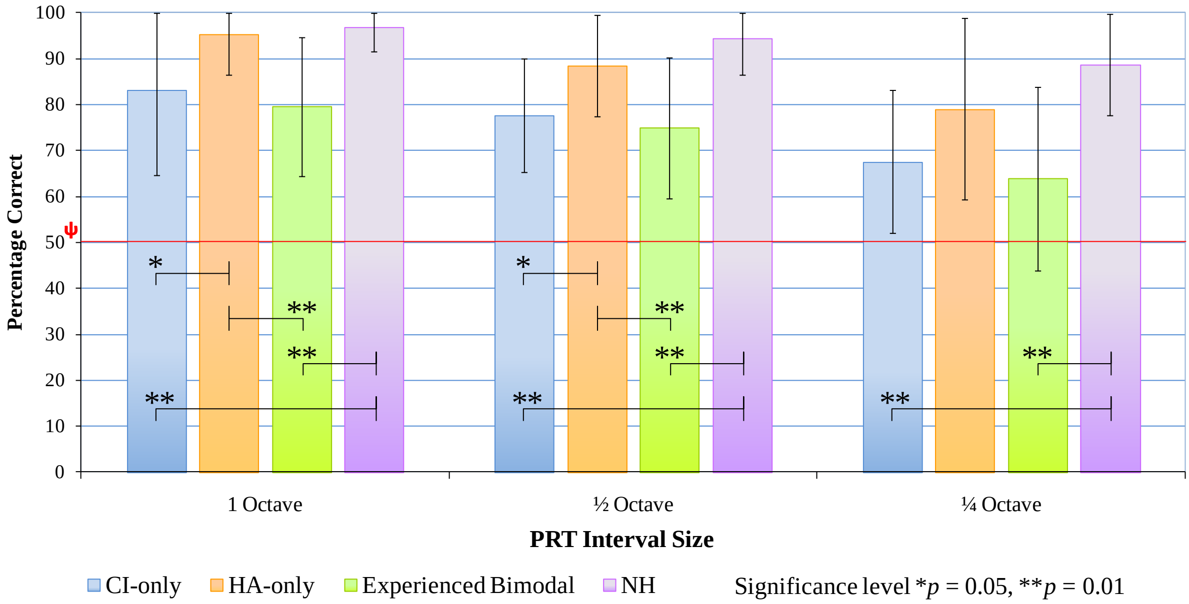

***Figure 6.5*:** **Summary of between-group differences for the Pitch Ranking Task.**
ψIndicates the level of chance performance.
Error bars represent ± one standard deviation from the mean.

One-way repeated measures ANOVAs were also conducted for each group to determine the effect of subtest on within-group PRT performance (see *Figure 6.6*). The effect of subtest was significant for all four groups: CI-only ($F(2, 65) = 5.492$, $p = 0.006$); HA-only ($F(2, 53) = 5.84$, $p = 0.005$); eBM ($F(2, 63) = 3.26$, $p = 0.045$); NH ($F(2, 87) = 7.36$, $p = 0.001$). Post-hoc analysis using Bonferroni (CI-only and eBM groups) or Tamhane T2 (HA-only and NH groups) corrections revealed that all groups scored significantly lower on the ¼ octave subtest than the 1 octave subtest: CI-only ($p = 0.005$); HA-only ($p = 0.016$); eBM group ($p = 0.039$); NH ($p = 0.002$). There were no significant differences in scores between the 1 and ½ octave subtests, or the ½ and ¼ octave subtests for any group. In summary, all groups scored significantly worse on the ¼ octave than the 1 octave subtest.

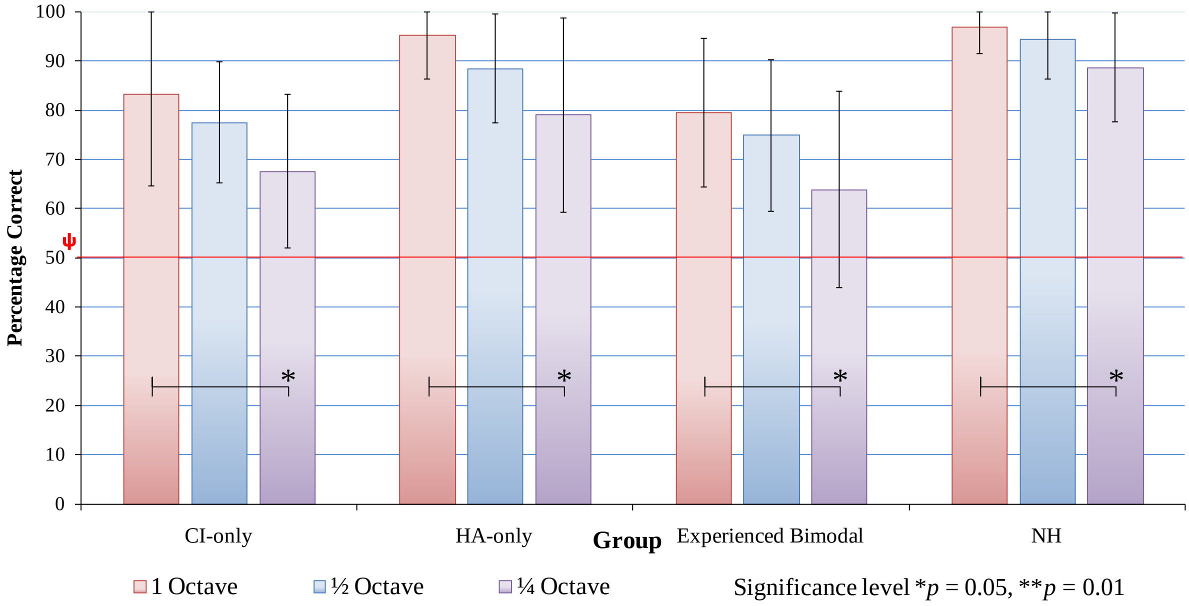

Figure 6.6: **Summary of between-condition differences for the Pitch Ranking Task.**
All groups scored significantly better on the 1 octave subtest than the ¼ octave subtest.
ψIndicates the level of chance performance.
Error bars represent ± one standard deviation from the mean.

As discussed in section 2.4, Dorman et al. (2008) reported that the proportion of adult BMS users who scored ≥ 85% correct on an arrhythmic melody recognition task (53%) was significantly greater than the proportion of CI-only users that did the same (11%). Given that Looi et al. (2008) reported moderate correlations between melody recognition scores and PRT scores for unilateral CI users, it was worthwhile determining whether a similar outcome was evident in the data of the present study. An overview of the distribution of scores for each subtest indicated that it was unlikely that statistical analysis would provide evidence to support this, as the number of high-scoring eBM users was less than or equal to the number of high-scoring CI-only users (see Figure 6.7). However, this visual summary did highlight the performance of participant D009, whose mean PRT scores were >90% correct across all subtests (see dashed line Figure 6.7).

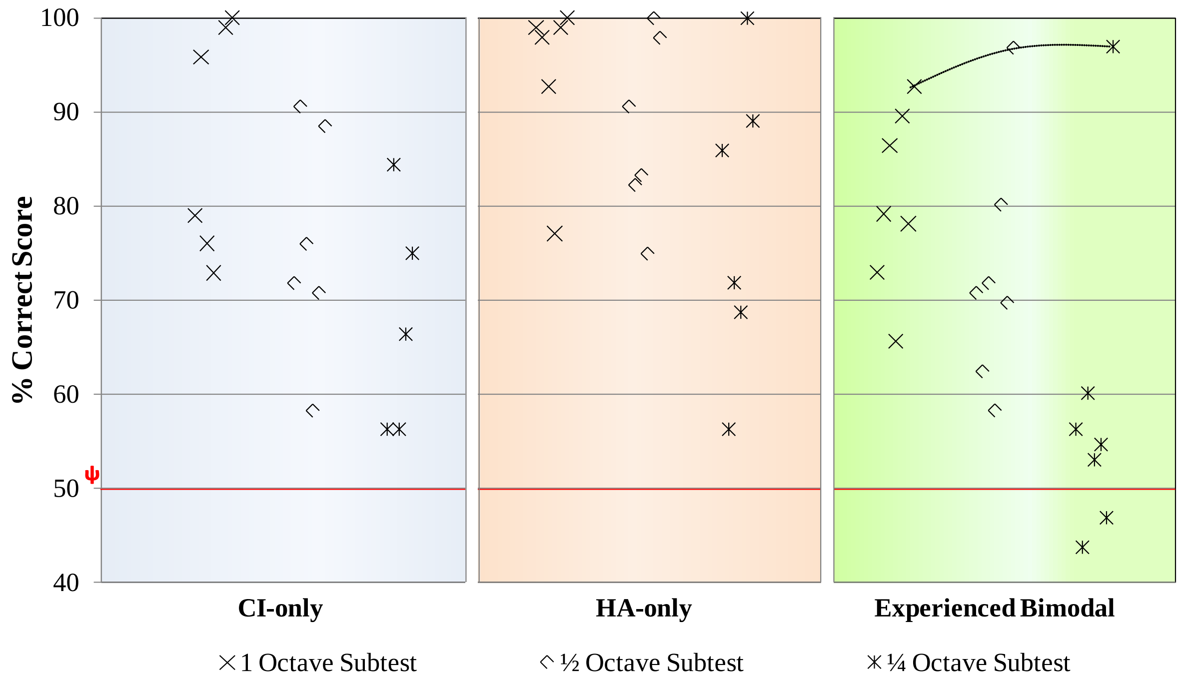

Figure 6.7: **Distribution of the mean Pitch Ranking Task scores of participants in the CI-only, HA-only and eBM groups.**

ΨIndicates the level of chance performance.

6.5 Questionnaire

The Parental Perceptions of Listening Device Performance Questionnaire (PPLDPQ) was completed by the parents of all hearing-impaired children in the study as indicated in section 5.5.2. As statements were worded in both the positive and the negative, ratings were scored so that '1' always represented the worst outcome, and '5' always represented the best outcome for each question. For example, if a parent/caregiver "strongly agreed" with the statement "My child often removes their hearing devices complaining that sounds are too loud" the response would be given a score of '1', indicating an undesirable outcome. Conversely if they "strongly disagreed" with the statement, the response would receive a score of '5' as this is a positive outcome. For the statement "my child wears their hearing devices for more than 80% of the day" ratings of "strongly agree" would be given scores of '5' (positive outcome) and ratings of "strongly disagree" would be given a score of '1' (negative outcome). If parents neither agreed nor disagreed with a statement, their neutral position was represented by a score of '3'. A summary of results is available in Table 6.5

and *Figure 6.8*. For brevity, the music & fine-structure subdomains title has been shorted to 'fine structure.'

	Device Usage		Fine Structure		Environmental Awareness		Speech in Quiet		Speech in Noise	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
CI-only	4.52	0.42	3.69	0.59	3.91	0.64	3.75	1.07	3.51	1.04
HA-only	4.19	0.31	3.72	1.11	2.62	0.89	2.65	0.91	2.67	1.07
eBM	4.05	0.53	3.96	0.51	3.84	0.78	3.64	0.79	3.23	0.77

Table 6.5: Mean group Questionnaire ratings.

Range = 1.0 to 5.0 for all categories
The responses for each question were given equal weighting when calculating these means, i.e. no one single question had a greater influence in determining a group's mean on any subdomain.

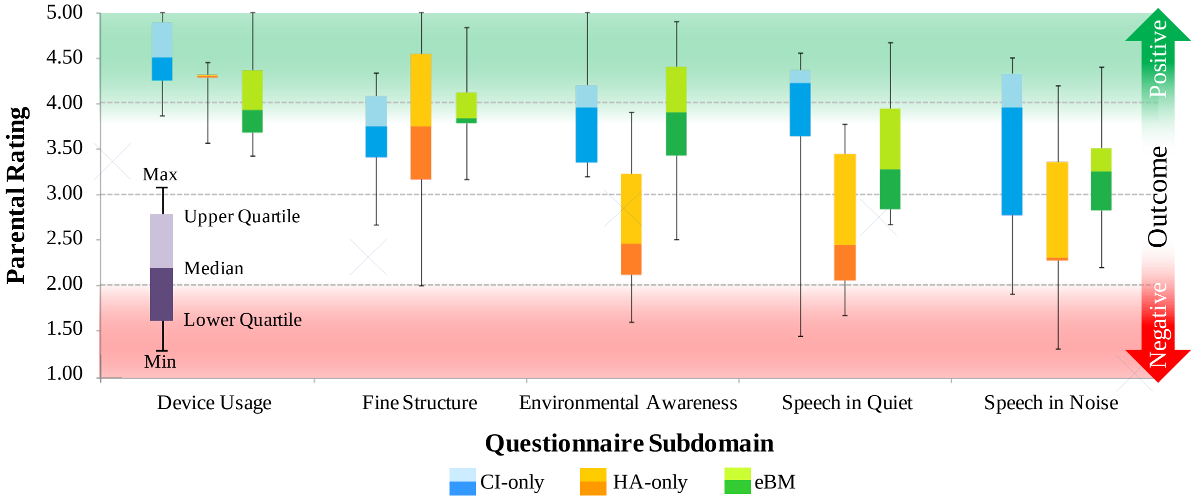

***Figure 6.8*: Distribution of mean ratings for each PPLDPQ subdomain, for each subject group.**

NB: for the device usage subdomain, the distribution of mean ratings for the HA group was so small that the upper and lower quartiles and median were equal.

For the device usage subdomain, children in the CI-only group obtained the highest ratings, children in the eBM received the lowest ratings (see Table 6.5). For the fine structure subdomain the median rating for the eBM group was highest, although this measure was similar for all groups (see Table 6.5). The maximum rating of the HA-only group on the environmental awareness subdomain was lower than the median ratings of the CI-only and eBM groups. Children in the CI-only and HA-only groups were rated the highest and lowest respectively, on both the speech in quiet and speech in noise subdomains.

Overall, the parent/caregiver(s) of children in the CI-only (M = 3.88, SD = 0.39) and eBM groups (M = 3.71, SD = 0.39) rated their child's performance with their listening devices higher than the parent/caregiver(s) of children in the HA-only group (M = 3.17, SD = 0.74).

A two-way RM ANOVA was performed in order to determine whether the effects of group or subdomain were significant in the ratings provided. A significant effect was found for subdomain ($F(4, 91) = 9.314$, $p < 0.001$) but not group ($F(2, 93) = 2.637$, $p = 0.98$), with a significant interaction between these factors ($F(8, 87) = 2.115$, $p = 0.044$). Separate one-way RM ANOVAs performed to investigate the source of the significant interaction revealed a significant between-group difference for parental ratings on the environmental awareness subdomain ($F(2, 19) = 5.395$, $p = 0.010$). Post-hoc analysis using Bonferroni corrections revealed that the parents of children in the HA-only group ranked their children lower than the parents of children in the CI-only ($p = 0.016$) and eBM groups on the environmental awareness sub-scale ($p = 0.024$; see *Figure 6.8*). There were no significant between-group differences in parental ranking for the overall questionnaire score, or the speech in quiet, speech in noise, device usage and fine structure subdomains. One-way ANOVAs were conducted to check for any within-group differences in parental ratings across subdomains. There were no significant differences between the mean ratings of parents on each subdomain for the CI-only, HA-only or eBM groups.

6.6 Correlations

Non-parametric Spearman's rho (ρ) correlation coefficients were calculated in order to investigate potential relationships between:

- CNC, HINT and PRT scores.
- CNC, HINT and PRT scores and parental ratings on the PPLDPQ.
- CNC, HINT and PRT scores and subject variables that have previously been shown to have some relationship with performance on similar tasks including: chronological age, age at implantation, duration of listening device usage, low-frequency BE PTA

(mean of unaided thresholds at 0.25, 0.5 and 1 kHz), speech-frequency PTA (mean of unaided thresholds at 0.5, 1, 2 kHz) and musical experience level (MEL) (Andrews & Madeira, 1977; Blamey et al., 2001; Büchner et al., 2009; Duell & Anderson, 1967; Eisenberg et al., 2004; El Fata et al., 2009; Stalinski et al., 2008; Sucher & McDermott, 2007; Svirsky & Meyer, 1999).

For these correlations, the following summary scores were calculated for each participant in the CI-only, HA-only and eBM groups:

- Mean CNC words correct (average of session 1 and session 2 scores);
- Mean HINT sentences in quiet correct (average of session 1 and session 2 scores);
- Mean HINT sentences in noise correct (average of session 1 and session 2 scores for the S0N0, S0NCI and S0NHA conditions), and;
- Mean PRT score (average of PRT scores from all sessions and subtests).

Correlations for the NH group were excluded from the above analyses as it was not expected that the aforementioned subject variables would apply to this group, with the exception of MEL. Separate analyses were used to investigate whether there was any relationship between MEL and mean PRT scores for the NH group.

6.6.1 Correlations between Test Scores

For the hearing-impaired groups, strong correlations were found between scores on the CNC word lists and; HINT sentences in quiet (ρ = 0.769, p < 0.001), and; the HINT sentences in noise (ρ = 0.776, p < 0.001). Significant correlations were also found between HINT sentence scores in quiet and in noise (ρ = 0.738, p < 0.001). No significant correlations were found between mean PRT scores and; mean CNC word scores, or; mean HINT sentence in quiet scores, or; mean HINT sentence in noise scores.

6.6.2 Correlations between Test Scores and Subject Variables

For the hearing-impaired groups, no significant correlations were found between chronological age and mean PRT scores. In addition, no significant correlations were found between MEL and mean scores on the CNC word lists or HINT sentences in quiet or noise, however, a moderate positive correlation was found between MEL and mean PRT scores (ρ = 0.628, p = 0.002). A weak positive correlation was found between age at hearing loss diagnosis and mean PRT scores (ρ = 0.486, p = 0.025). No significant correlations were found between the subject variables of chronological age or duration of listening device usage and mean scores for any of the perceptual tests used in the present study.

Correlations between unaided hearing thresholds and test scores were performed using data from the HA-only and eBM groups only. There were no significant correlations between BE unaided PTAs (low- or speech-frequency) and mean scores for the CNC words or HINT sentences in quiet or noise. A moderate negative correlation was found between speech-frequency BE unaided PTA and mean PRT scores (ρ = -0.455, p = 0.028). A stronger moderate negative correlation was found between low-frequency PTA and mean PRT score (ρ = -0.678, p = 0.011; see *Figure 6.9*).

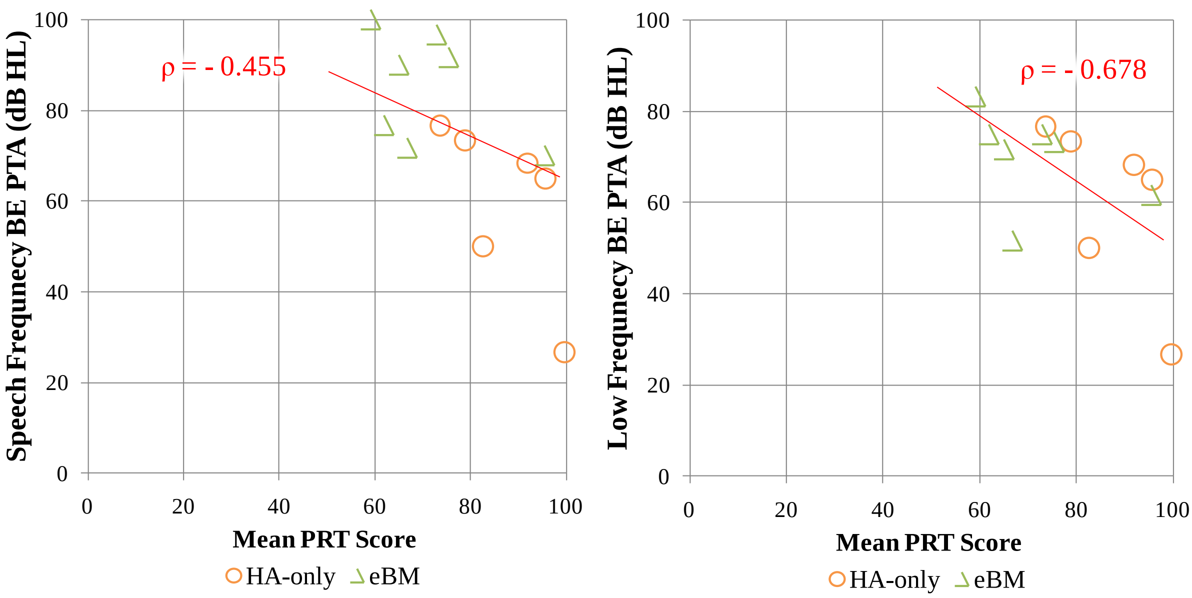

Figure 6.9: **Low-frequency better-ear unaided PTA versus mean PRT scores.**

For the NH group, a moderate positive correlation was found between MEL and mean PRT scores (ρ = 0.676, p = 0.006; see *Figure 6.10*).

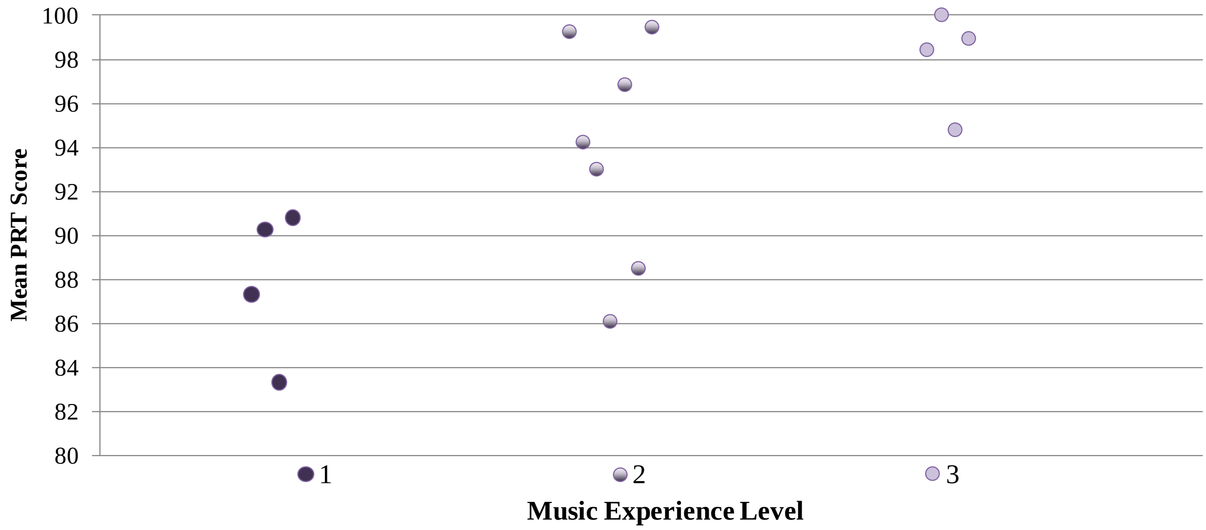

Figure 6.10: **Distribution of mean Pitch Ranking Task scores for the NH group according to Music Experience Level.**

1: no participation in formal or classroom musical training. 2: < 2 years of participation in formal music training or classroom musical lessons. 3: ≥ 2 years of formal music training and/or classroom music lessons.

As reported in section 6.4.3, participant D009 was one of only two hearing-impaired participants who scored > 90% correct on all three PRT subtests. D009 was the oldest member of the eBM group. Given that the eBM group was significantly younger (M = 9.24 years) than the CI-only group (M = 12.92 years; p = 0.036), and had very poor residual hearing, it is possible that maturation of their central auditory nervous system may have been delayed in regards to pitch discrimination. Additional analyses revealed a strong correlation between mean PRT scores and the chronological age of participants in the eBM group (ρ = 0.714, p = 0.036; 1-tailed test; see *Figure 6.11*). A 1-tailed test was used as pitch ranking performance increases with increasing age and central auditory maturation (Stalinski et al., 2008).

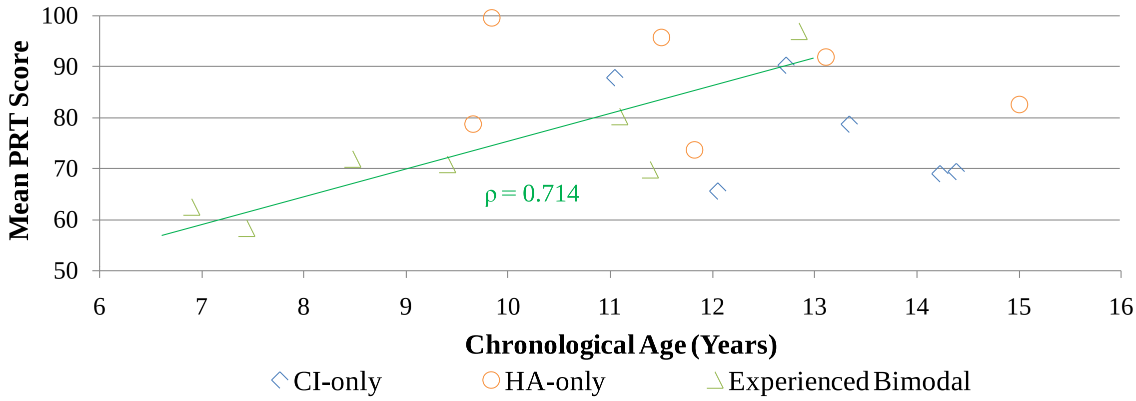

Figure 6.11: **Correlation between chronological age and mean PRT scores for the eBM group.**

6.6.3 Correlations between Test Scores and Questionnaire Ratings

Mean CNC word scores were moderately correlated with PPLDPQ ratings for the speech in quiet (ρ = 0.490, p = 0.024; see *Figure 6.12*) and environmental awareness subdomains (ρ = 0.491, p = 0.011), and moderately correlated with PPLDPQ ratings for the speech in noise subdomain (ρ = 0.545, p = 0.024). No significant correlations were found between; mean HINT sentence in quiet scores and PPLDPQ ratings; mean HINT sentence in noise scores and PPLDPQ ratings, or; mean PRT scores and PPLDPQ ratings across all five subdomains.

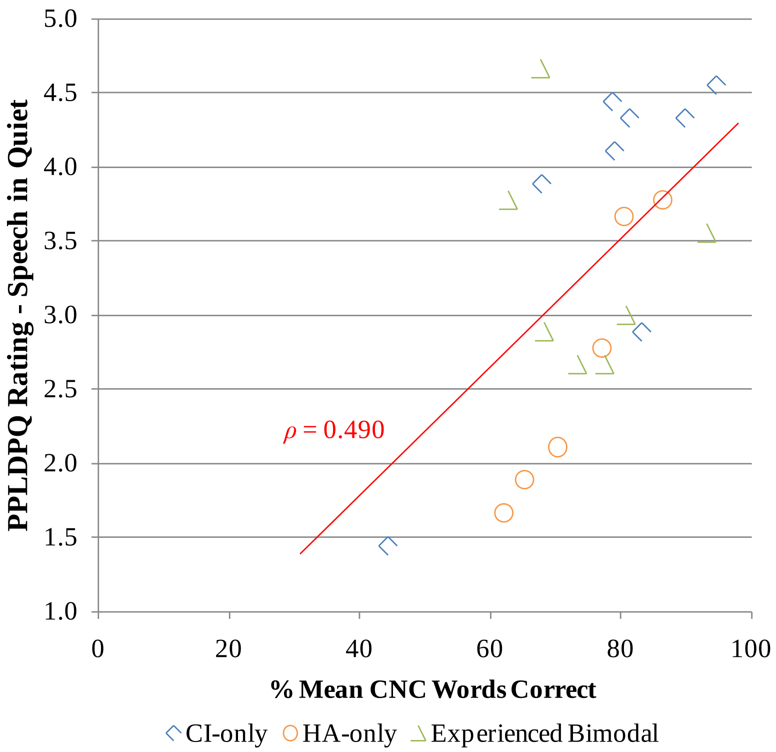

Figure 6.12: **Correlation between Questionnaire ratings for the speech in quiet subdomain and mean CNC words correct scores.**

6.7 New Bimodal Case Study (Case A)

As only one new-bimodal participant, referred to from this point as “Case A”, participated in this study, statistical analysis was not possible. To provide some context for comparisons of A’s performance on the CNC words, HINT sentence and PRT under CI-only and BMS conditions, score difference residuals (SDR’s) were calculated for participants in the CI-only, HA-only and eBM groups.

SDR’s were calculated by subtracting a participant’s session 1 score from their session 2 score for a task. A positive SDR indicates an improvement in scores from session 1 to session 2, whereas a negative SDR indicates a decrease in scores from session 1 to session 2. Where participants scored at ceiling levels (100% correct) on a particular task at *both* testing sessions, the resulting SDR was excluded from any analyses, as inclusion would have resulted in the underestimation of the magnitude of the median SDR. By calculating SDRs for each group, we are able determine whether the addition of a contralateral HA resulted in an improvement in scores that was greater than the size of learning effects present for the other groups.

CNC word list and HINT sentence SDRs were not calculated for the eBM group as session 1 scores were invalidated due to differences in testing protocols, as discussed earlier (see section 6.3). A summary of Case A’s results is provided in Table 6.6. A summary of the mean SDRs for the CI-only, HA-only and eBM groups is provided in Table 6.7.

Task	CI-only	BMS	SDR
CNC Words (% Correct)			
Words	44.00	39.58	- 4.42
Phonemes	68.00	65.33	- 2.67
HINT Sentences (% Correct)			
S0	66.26	90.10	23.74
S0N0	69.52	80.00	10.48
S0NCI	45.10	50.96	5.86
S0NHA	51.92	71.29	19.36
Pitch Ranking Task (% Correct)			
1 Octave, Female	87.50	100.00	12.50
1 Octave, Male	75.00	95.83	20.83
½ Octave, Female	87.50	87.50	0.00
½ Octave, Male	66.67	79.17	12.50
¼ Octave, Female	71.88	75.00	3.13
¼ Octave, Male	56.25	62.50	6.25

Table 6.6: Summary of scores and score difference residuals for Case A.

Task	CI-only	HA-only	BMS
CNC Words (SDR, % Correct)			
Words	-4.99	2.67	N/A
Phonemes	-0.45	-3.66	N/A
HINT Sentences (SDR, % Correct)			
S0	-0.71	-5.72	N/A
S0N0	-4.49	-1.00	N/A
S0NCI	5.28	3.57	N/A
S0NHA	3.21	5.59	N/A
Pitch Ranking Task (SDR, % Correct)			
1 Octave, Female	15.63	8.33	27.10
1 Octave, Male	6.83	4.17	11.66
½ Octave, Female	0.00	12.50	-2.09
½ Octave, Male	0.00	15.28	5.74
¼ Octave, Female	3.75	34.38	15.36
¼ Octave, Male	8.59	18.75	5.53

Table 6.7: Summary of the score difference residuals for hearing-impaired groups.

6.7.1 Speech Recognition Tests

Case A's CNC word and phonemes correct scores dropped by 4.4% and 2.0% respectively when tested using BMS compared to their initial performance using their CI-only (see *Figure 6.13*). On the HINT sentences task, Case A showed improved performance in the BMS condition, total scores increasing by 27.3 % points for sentences in quiet, and by between 5.7 and 19.4 % points for sentences in noise (see *Figure 6.13* and Table 6.6).

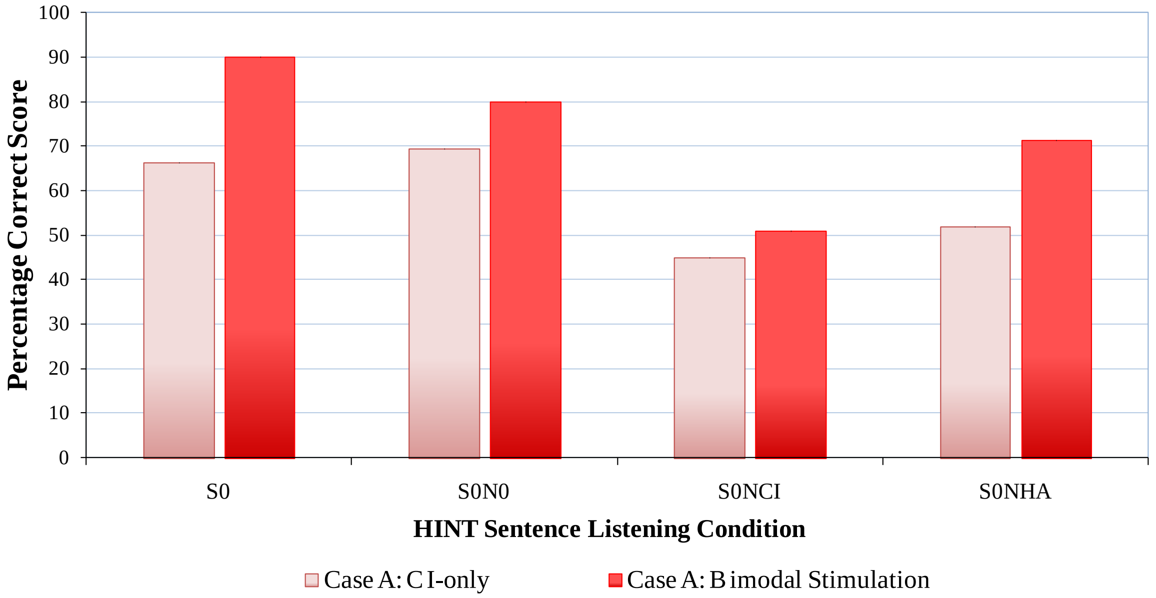

***Figure 6.13:* Summary of speech recognition scores for Case A.**

The improvements in Case A's HINT sentence scores in the bimodal condition were greater than the maximum SDR's for the CI-only and HA-only groups for the S0, S0N0 and S0NHA conditions, and close to or above the 75th percentile SDR for the CI-only and HA-only groups for the S0NCI condition (see *Figure 6.14*). Overall, Case A showed an improvement in HINT sentence scores that was greater than that seen in the CI-only and HA-only groups.

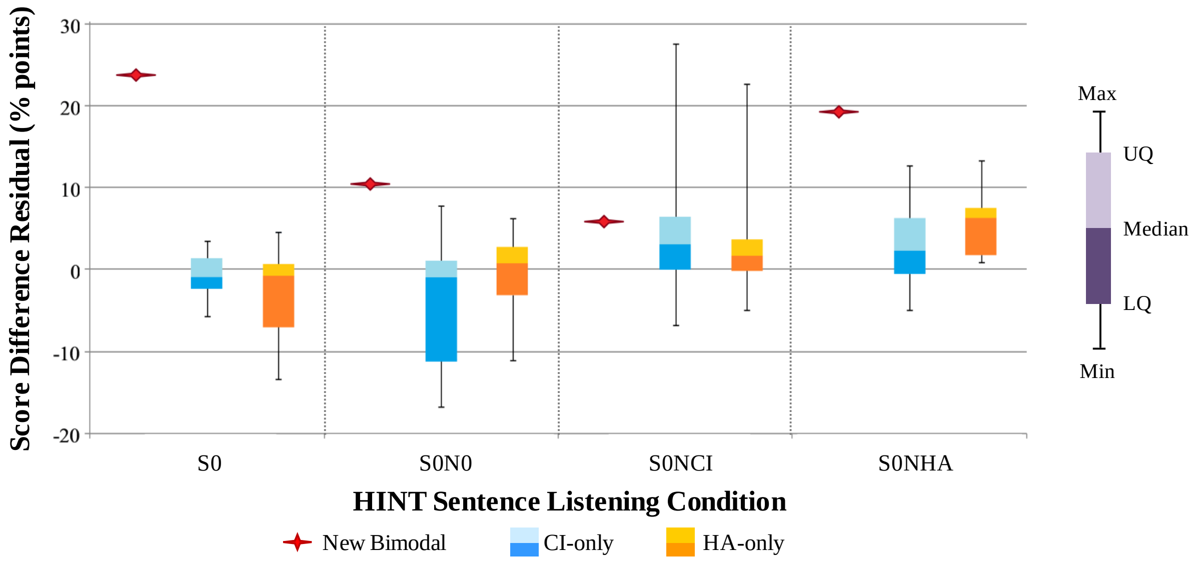

Figure 6.14: **HINT sentence SDR comparison: Case A versus the CI-only and HA-only groups.** UQ = Upper Quartile, LQ = Lower Quartile.

6.7.2 Pitch Ranking Task

Following the addition of a contralateral HA, Case A's scores improved by an average of: 16.5 % points for the 1 octave subtest; 6.25 % points for the ½ octave subtest; and 4.69 % points for the ¼ octave subtest. The degree of improvement was greater for male-sung than female-sung stimuli (see *Figure 6.15*).

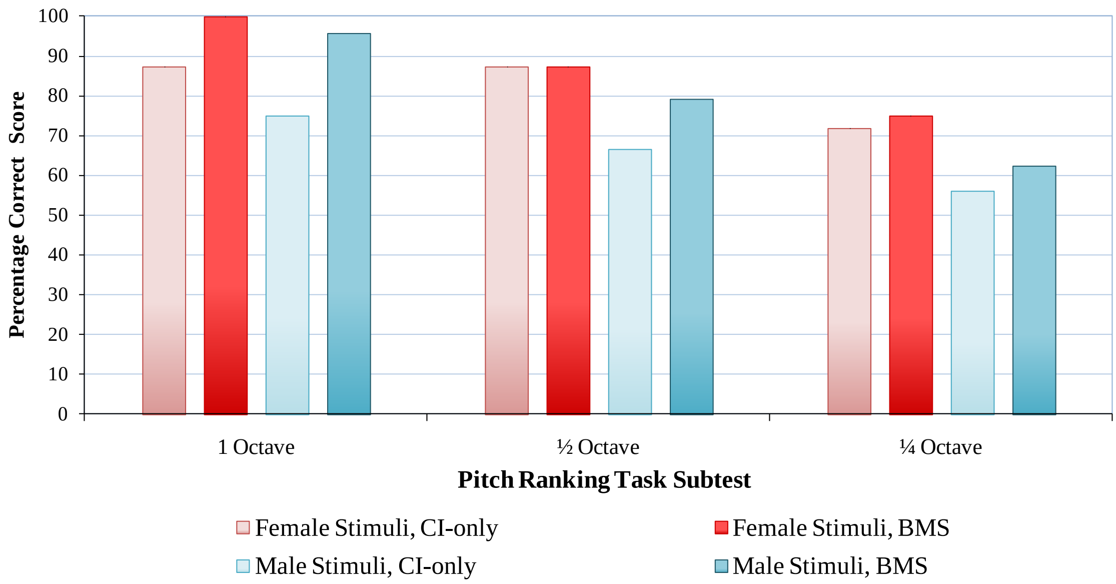

Figure 6.15: **Summary of Pitch Ranking Task scores for Case A.**

Case A's mean PRT scores in the CI-only condition were nearly equivalent to those of the CI-only and eBM groups for all three subtests (see *Figure 6.16*). In the bimodal condition, Case A's mean PRT score was greater than mean scores of all hearing impaired groups for the1 octave subtest, and greater the mean scores of the CI-only and eBM groups for the ½ and ¼ octave subtests (see *Figure 6.16*).

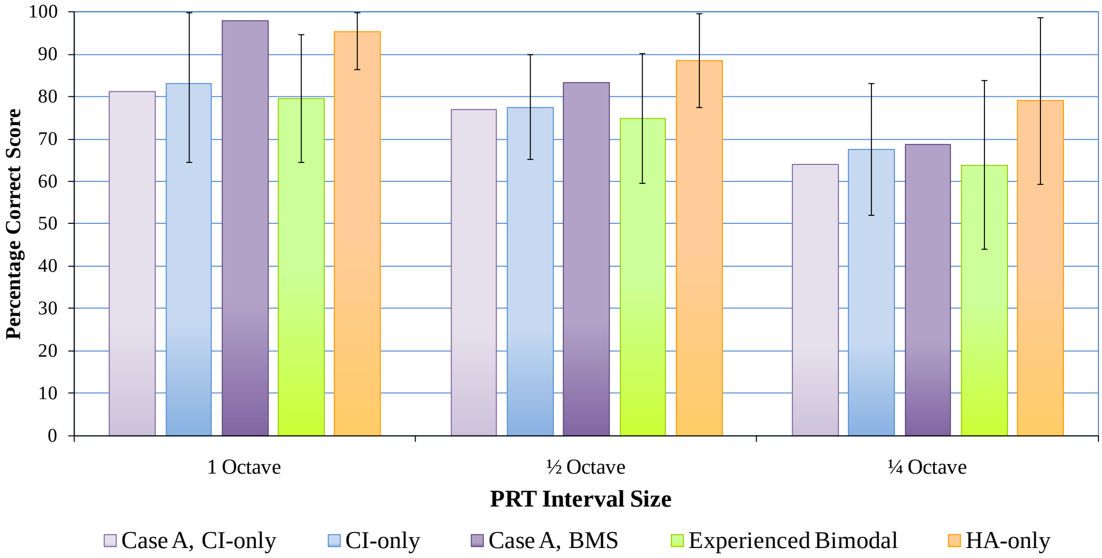

Figure 6.16: **Pitch Ranking Task score comparison: Case A versus hearing-impaired groups.** Error bars represent ± one standard deviation.

For male-sung stimuli, Case A scored higher in the bimodal condition than the CI-only condition on all three PRT subtests (see Table 6.6, *Figure 6.15* and *Figure 6.17*). For the 1 octave interval size, male-sung stimuli, Case A's SDR was greater in magnitude than any learning effect seen in the CI-only and HA-only groups and above the median SDR of the eBM group (see *Figure 6.17*). For the ½ octave subtest, male-sung stimuli, Case A's SDR was greater than the maximum SDR for the CI-only group and greater than the 75th percentile SDR for the eBM group, but less than the median SDR of the HA-only group (see *Figure 6.17*). For the ¼ octave subtest, male-sung stimuli, Case A's SDR was above the median SDR of the CI-only group, but less than the median SDR of the HA-only and eBM groups. In summary Case A's SDRs were greater in magnitude than the largest SDRs seen in the CI-only group for the 1 and ½ octave subtests. Improvements at these interval sizes were greater in magnitude than the size of any learning effects seen for the CI-only group.

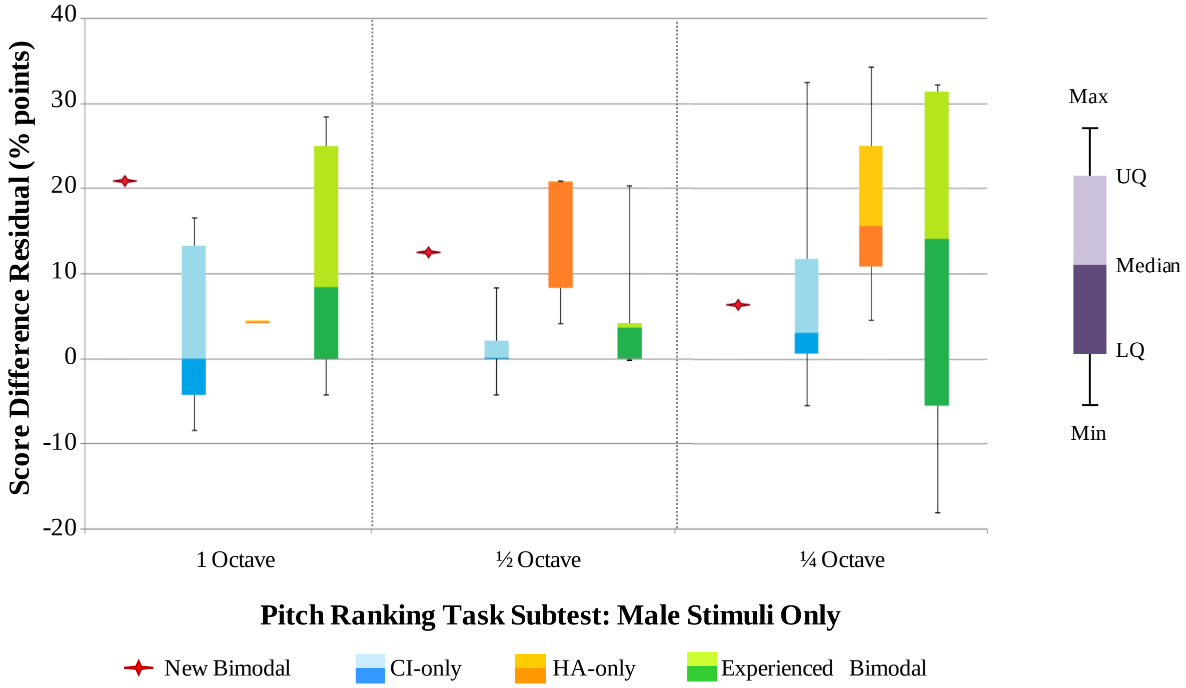

***Figure 6.17*: Comparison of the Pitch Ranking Task SDRs: male stimuli only.**

UQ: Upper Quartile; LQ: Lower Quartile.
NB: The score difference residuals for the HA-only group were the same for all participants on the 1 octave subtest, and the median, upper quartile and maximum values were all the same.

Case A showed less of an improvement in PRT performance for female-sung stimuli. Case A's SDR on the 1 octave subtest, for female-sung stimuli, was greater than the 75th percentile SDR of the HA-only group, between the median and 75th percentile SDR of the CI-only group, and less than the minimum SDR of the eBM group (see *Figure 6.18*). Case A's SDR was zero on the ½ octave subtest, female-sung stimuli. The increase in Case A's score on the ¼ octave subtest was less than the minimum SDRs for the HA-only and eBM groups, and less than the median SDR of the CI-only group (see *Figure 6.18*). In summary Case A's SDRs were similar to those of the CI-only group across all subtests for female-sung stimuli.

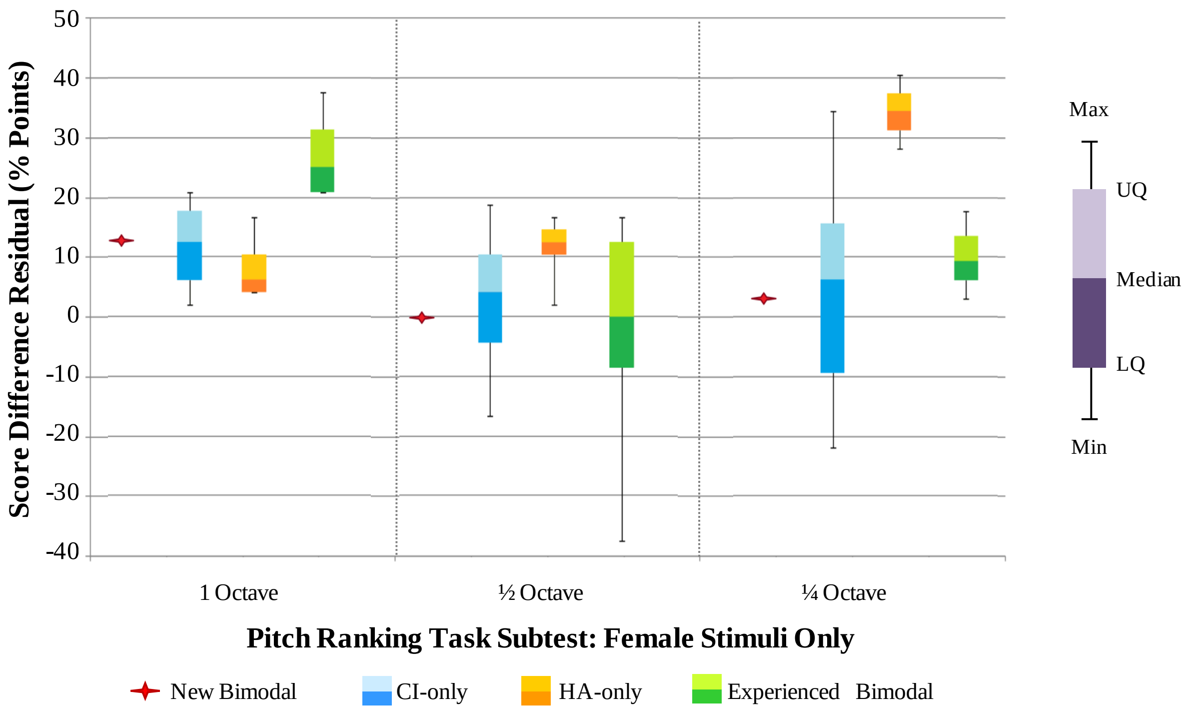

Figure 6.18: **Comparison of the Pitch Ranking Task SDRs: female stimuli only.**
UQ = Upper Quartile, LQ = Lower Quartile.

In summary, Case A's SDRs for female-sung stimuli were of a similar magnitude to the changes seen for the CI-only group on all three PRT subtests, suggesting that any improvements in score for female-sung stimuli were likely due to a learning effect. However, for male-sung stimuli, Case A's SDRs were larger than those of the CI-only and HA-only group for the 1 octave subtest and larger than the CI-only group for the ½ octave subtest. This indicates that the addition of a contralateral HA resulted in improvements in Case A's PRT scores that were greater in magnitude than any learning effects seen in the CI-only only and HA-only groups for male-sung vowels.

6.7.3 Questionnaire Ratings

The parents of Case A completed the PPLDPQ prior to, and four months after their child was fitted with a contralateral HA. Ratings improved for the speech understanding in noise, and music and fine structure subdomains following Case A's switch to BMS (see Table 6.8). Fewer maximum performance ratings (a score of 5) meant that the mean rating for the speech understanding in quiet subdomain fell slightly, however ratings were positive overall. Scores also dropped for the device usage subdomain. Overall, the parents of Case A gave a positive appraisal of their child's performance with their listening device(s), giving ratings of ≥ 4 for all but one subdomain.

	Device Usage	**Speech Understanding in Quiet**	**Speech Understanding in Noise**	**Environmental Awareness**	**Music and Fine Structure**
CI-only	4.86	4.56	3.70	4.60	4.33
BMS	4.00	4.11	4.40	4.60	4.83

Table 6.8: Summary of Case A's mean ratings for each Questionnaire subdomain.

7 Discussion

The purpose of the present study was to compare the performance of children using a unilateral CI (CI-only), BMS, or bilateral HAs[12] (HA-only) on tasks of speech recognition in quiet and noise and a pitch ranking task. It was hypothesised that:

1. For tasks of word recognition in quiet, children who use BMS will score higher than children using a CI-only. HA-only and CI-only users will score at similar levels;

2. For tasks of sentence recognition in quiet, children who use BMS, a CI-only, or HA-only will score at similar levels[13];

3. For tasks of sentence recognition in noise, child users of BMS and HA-only users will score higher than their CI-only counterparts;

4. When ranking pitch, children who use BMS will score higher than those using a CI-only, but not children who use bilateral HAs, and;

5. That the addition of an optimally fitted HA in the non-implanted ear of children using a CI will result in better performance in tests of speech recognition in quiet and noise, and pitch perception.

Our results provide only weak evidence in support of our first hypothesis. Although there was no significant difference between the mean CNC word recognition scores of the CI-only (M = 71.87), HA-only (M = 65.39), and eBM groups (M = 76.45), a significantly greater proportion of eBM users (80%) obtained scores of ≥ 80% correct on this task, than the proportion of CI-only (25%; p = 0.038) and HA-only users (16.7%; p = 0.022) who did the same. Consistent with our second hypothesis, we found no significant difference between the mean HINT sentence in quiet scores of the CI-only (M = 92.7%), HA-only

[12] With severe to profound bilateral SNHL.

[13] Due in part to the increased redundancy of sentences compared to words in quiet.

(*M* = 95.64%), and eBM groups (*M* = 95.74%). Contrary to our third hypothesis, we found no significant differences between the mean HINT sentence recognition in noise scores of the CI-only, HA-only and eBM groups, with participants from all three groups scoring at ceiling levels across all three (S0N0, S0NCI, S0NHA) listening conditions. Our results are only partially consistent with our fourth hypothesis. Unexpectedly, we found no significant differences between the mean scores of the eBM and CI-only group for all three PRT subtests. However, the HA-only group scored significantly higher than the CI-only group on the 1 (p = 0.035) and ½ octave subtests (p = 0.026) as predicted. Consistent with this, the HA-only group also scored significantly higher than the eBM group, on the 1 ($p < 0.001$) and ½ octave subtests ($p < 0.008$). Finally, consistent with our fifth hypothesis, Case A's sentence recognition in quiet and noise scores, and PRT scores for male-sung stimuli increased markedly following the addition of a contralateral HA.

7.1 Speech Recognition

7.1.1 CNC Word Lists

7.1.1.1 Between-Group Differences

Contrary to our first hypothesis, we found no statistically significant difference between the mean CNC scores of the CI-only (*M* = 71.87) and eBM groups (*M* = 76.45). This finding was unexpected, as the general consensus among within-group comparison studies[14] is that the addition of a contralateral HA to unilateral CI-users with residual acoustic hearing in their non-implanted ear results in improved word recognition performance (Ching et al., 2001; Dunn et al., 2005; Mok et al., 2006). However, we did find that the proportion of eBM users (80%) who obtained scores of ≥ 80% correct was significantly larger than the proportion of CI-only (25%; p = 0.038) and HA-only users (16.7%; p = 0.022) who did the same. This finding is along similar lines to the results of Dorman et al. (2008) who found that the proportion of high-performing adults using BMS was greater than the proportion of

[14] One participant group assessed using BMS and CI-alone.

high-performing unilateral CI users on a range of speech recognition tasks (see section 3.3). However, our findings should be interpreted with caution due to a range of factors that may have confounded comparisons made between the CI-only and eBM groups.

Firstly, the eBM group all used the newer Freedom speech processor, while 7 of the 8 CI-only participants used its predecessor, the ESPrit 3G. Features that differ between two processors are described in section 2.3.1. Of these, the Instantaneous Input Dynamic Range[15] (IIDR) and Adaptive Dynamic Range Optimisation (ADRO) are potential confounding factors.

The Freedom processor has a maximum IIDR of 40 dB, increased from 30 dB in the ESPrit 3G. Numerous studies have indicated that increasing the IIDR from 30 dB to 40 dB improves adult CI's users recognition of low-level consonants and words (Dawson, Vandali, Knight, & Heasman, 2007; James et al., 2003; Spahr, Dorman, & Loiselle, 2007). Davidson et al. (2009) assessed the CNC word recognition abilities of 30 child CI users (Nucleus CI24; Freedom Processor), using IIDRs of 30 dB and 40 dB. Stimuli were presented at 60 dBSPL. Results indicated that there was no significant advantage for an IIDR of 40 dB for speech presented at levels of 60 dBSPL. Given that a presentation level of 65 dBSPL was used in the present study, it is less likely that any processor-specific IIDR differences between the CI-only and eBM groups resulted in a significant advantage for the latter.

The Freedom processor also includes Adaptive Dynamic Range Optimisation (ADRO; described in section 2.3.1), a feature not available in the ESPrit 3G. James et al. (2009) reported a significant improvement (M = 9.5%) in the CNC word recognition in quiet scores of adult CI users (n = 9; Nucleus CI24; ACE, SPEAK) when using ADRO. All Freedom processor users in the present study had ADRO pre-programmed into their MAPs. Unfortunately MAPs could not be altered due to restrictions placed upon ethical approval,

[15] The instantaneous input dynamic range is the range of acoustic input levels mapped to a user's electrical dynamic range, at any point in time.

and at the request of clinicians. It is possible that ADRO may have contributed to the superior word recognition performance of the eBM group.

The performance of participants in the CI-only and eBM groups may have also varied according to the speech processing strategy used. Several studies comparing CNC word recognition performance of children using the SPEAK and ACE strategies have reported significant advantages for the latter (Pasanisi et al., 2002; Psarros et al., 2002). Psarros et al. (2002) (*n* = 9) reported a mean 8.3 % point advantage in favour of the ACE strategy. Pasanisi et al. (2002) (*n* = 7) reported a 22.2 % point advantage in favour of the ACE strategy. However, the aforementioned studies looked only at performance differences in the short term. Manrique et al. (2005) compared the speech recognition abilities of separate groups of children programmed using the ACE (*n* = 26; Nucleus CI24) and SPEAK (*n* = 32; Nucleus CI24) strategies. Although the ACE group scored significantly higher on tests of word recognition at 12 months post-switch-on, at 24 months there was no significant difference between the two groups. In the present study, 2 CI-only users were programmed using the SPEAK strategy, and both had more than 2 years device experience. It is therefore unlikely that the greater proportion of SPEAK users in the CI-only group resulted in any significant disadvantage in word recognition performance relative to their eBM counterparts.

It is worthwhile considering that the eBM group was significantly younger (*M* = 9.24 years) than the CI-only group (*M* = 12.92 years; *p* = 0.036), but more importantly, the eBM group also had significantly less experience using their listening devices (*M* = 3.95 years; *SD* = 3.51) than their CI-only counterparts (*M* = 7.26 years; *SD* = 3.51 years). As discussed in section 3.1.1, the speech recognition abilities of child CI users can continue to improve until 3 years of device usage for both pre-lingually and post-lingually deafened children regardless of the duration of deafness (Rotteveel et al., 2008). Taking this into account, it is possible that half of the participants in the eBM group had not yet attained optimal levels of speech recognition performance using their CIs, compared to only a quarter of the CI-only users, potentially lending additional credence to our findings. Overall, we found some evidence in support of the first part of our first hypothesis; that children who use BMS will score higher than children using a CI-only on tasks of word recognition.

Consistent with the second part of our first hypothesis we found no significant difference between the performance of the HA-only and CI-only groups. The significant difference between the proportion of high-scoring eBM users (80%) and HA-only users (16.7%; $p = 0.022$) is at least partly due to the greater audibility of high-frequency speech sounds provided via a CI.

7.1.1.2 New Bimodal Case Study (Case A)

Contrary to our fifth hypothesis, Case A's CNC word and phoneme scores did not increase significantly following the addition of a contralateral HA. Case A correctly identified 3 fewer words, and 4 fewer phonemes in the BMS condition relative to the CI-only condition. This result was likely confounded by the order of test administration. The CNC word lists were administered first in the CI-only testing session, but at the end of the 90 minute BMS testing session, when the participant was possibly becoming fatigued.

7.1.2 HINT Sentences

7.1.2.1 Between-Group and Between-Condition Differences

Consistent with our second hypothesis, we found no significant difference between the sentence recognition in quiet scores of the CI-only ($M = 92.97\%$), HA-only ($M = 96.64\%$), and eBM ($M = 95.74\%$) groups. This result is consistent with previous studies reporting no significant difference between the sentence recognition in quiet scores of BMS and CI-only users (Dorman et al., 2008; Gifford et al., 2008), nor between CI-only and HA-only users with severe SNHL (Flynn et al., 1998).

The HINT sentences were also presented: (i) in spatially coincident multi-talker babble (S0N0); (ii) in spatially separated multi-talker babble presented to the better hearing (NH and HA-only groups) or implanted ear (CI-only and eBM groups; S0NCI), and; (iii) in spatially separated multi-talker babble on the side of the poorer hearing (NH and HA-only groups) or non-implanted ear (CI-only and eBM groups; see *Figure 5.5*); using a 10 dB SNR. The S0N0 condition assessed the ability of listeners to separate spatially co-incident speech from multi-talker babble, while the S0NCI and S0NHA assessed the role of head shadow effects in improving speech recognition performance.

Contrary to our third hypothesis, there was no significant difference between the scores of the eBM and CI-only groups, nor between the HA-only and CI-only groups for the S0N0, S0NCI and S0NHA listening conditions (see *Figure 6.2*). As discussed in section 3.1.2, the poor pitch resolution afforded by current CI technology means that unilateral CI users are unable to use F0 differences to segregate competing sounds or benefit from masking release (Oxenham, 2008; Stickney et al., 2004). In contrast, the acoustic hearing of adult users of BMS provides access to low-frequency pitch cues that allow for improved speech recognition in noise through the improved segregation of the F0 of target and competing talkers (Kong et al., 2004). It is unexpected that we found no significant differences between the mean sentence recognition in noise scores of the CI-only and eBM groups, nor between the proportion of 'high-scoring' CI-only and BMS users according to Dorman et al.'s (2008) criteria. Given that the HA-only group were likely to also have access to more-reliable pitch cues (Looi et al., 2008a, 2008b), it was also expected that the HA-only group would score higher than their CI-only counterparts.

At present the HINT test is the only sentence recognition test available with a New Zealand talker. The validity of the HINT sentences as a measure of open-set speech recognition in quiet was recently examined by Gifford et al. (2008). CI-only and BMS users were assessed using HINT and AzBio sentences, and CNC words in quiet. Data for the CNC words and AzBio sentences (see Table 7.1) was normally distributed no ceiling effects. BMS users scored significantly higher than their unilateral CI counterparts on both the CNC words and AzBio sentences. In contrast, results for the HINT sentences in quiet were positively skewed; 30.7% of the sample (including ⅔ of the BMS users) scored 100% correct, and 71%

of subjects scored ≥ 85% correct. No significant between-group differences in performance were found for the HINT sentence task. Further analyses revealed that CNC word scores were reasonable predictors of AzBio sentence scores but not HINT sentence scores. For example, an AzBio sentence score of ≥ 85% correct was associated with a CNC word score of between 66% and 94% correct. In contrast, HINT sentence score of 100% correct was associated with CNC word scores of between 20% and 94% correct. Gifford and colleagues (2008) concluded that the HINT sentence task was not a suitable tool for the assessment of speech recognition in quiet, and should only be administered in its intended adaptive format as per the recommendations of Luxford et al. (2001).

	CNC Word Lists		**HINT Sentences**		**AzBio Sentences**	
Group	*n*	*M*	*n*	*M*	*N*	*M*
Unilateral CI	162	55.7%	115	84.8%	49	72.1%
BMS	36	71.8%	15	94.1%	29	83.5%

Table 7.1: Select results from Gifford et al. (2008).

Overall, our findings are consistent with those of Gifford et al. (2008). The majority of the participants across all groups scored at ceiling levels for all four listening conditions (see *Figure 6.4*), hence the absence of any significant between-group differences in score for the CI-only, HA-only and eBM groups. Ceiling effects are also in part responsible for the absence of any significant between-condition differences across the CI-only, HA-only and eBM groups (see *Figure 6.3*). In addition, our results also bring into question the real-world validity of the HINT sentence scores and their relationship with parents' perceptions of their child's speech recognition performance. Significant correlations were found between CNC word and HINT sentence scores in quiet (ρ = 0.769, p < 0.001) and noise (ρ = 0.776, p < 0.001). Although CNC word scores were significantly correlated with parental ratings on the PPLDPQ for the speech in quiet (ρ = 0.490, p = 0.024) and speech in noise (ρ = 0.545, p = 0.024) subdomains, no significant correlations were found between the same parental ratings and mean HINT sentence scores in quiet or noise. Overall, our results indicate that the production of a New Zealand version of sentence recognition task with greater validity and difficulty is necessary for the future assessment of the speech recognition abilities of New Zealand CI and HA users.

Given that the HINT sentence test was designed for the assessment of hearing-impaired individuals, we expected ceiling level performances for the NH group. Consistent with this, the NH group obtained an overall mean score of 99.67% correct across the four listening conditions, and scored significantly higher than: the CI-only group for the S0N0, S0NCI and S0NHA listening conditions; the HA-only group for the S0N0 and S0NCI listening conditions, and; the eBM group for the S0N0 listening condition. However, due to the high proportion of ceiling scores in these results, and the relative ease of the task, our results are likely to underestimate the magnitude of difference in sentence recognition performance in noise between the NH and hearing-impaired groups.

7.1.2.2 New Bimodal Case Study (Case A)

Consistent with our fifth hypothesis, Case A's sentence recognition scores improved for all four listening conditions. For sentences in quiet, scores improved from 66.3% to 90.1% correct, an improvement of 23.7 % points. This gain was of a greater magnitude than the maximum SDR seen for CI-only and HA-only groups. This result is consistent with the results of comparable studies that showed a significant advantage for bimodal over electric-only stimulation for sentence recognition in quiet (Beijen et al., 2008; Ching et al., 2001, 2006, 2007; Dunn et al., 2005; Gifford et al., 2007; Luntz et al., 2003, 2005; Mok et al., 2006, 2007). Case A's improvement is probably at least in part attributable to the improved perception of low-frequency phonemes via their acoustic low-frequency hearing (Ching et al., 2001).

In noise, Case A's scores improved from: 69.5% to 80.0% correct for the S0N0 condition; 45.1% to 51.0% correct for the S0NCI condition, and; 51.9% to 71.3% correct for the S0NHA condition, following the addition of a contralateral HA. Case A's SDR for the S0N0 listening condition (10.5 % points) was larger than the maximum SDR of both the CI-only (7.8 % points) and HA-only groups (6.36 % points; see *Figure 6.14*). Case A's SDR for the S0NHA listening condition (19.36 % points) was also larger than the maximum SDR of both the CI-only (6.45 % points) and HA-only groups (5.79 % points; see *Figure 6.14*). Case A's SDR for the S0NCI condition (5.7 % points) was less than the maximum SDR of the CI-only (27.71 % points) and HA-only groups (21.0 % points), but still near their 75th percentile SDRs (6.41 and 3.75 % points respectively). Overall, our results are consistent with those of other within-group comparisons studies showing improved sentence recognition following the addition of a contralateral HA to the non-implanted ear of unilateral CI users due to improved access to binaural processing mechanisms (Ching et al., 2004; 2005; 2006; Mok et al., 2007; Morera et al., 2005) and the additional pitch cues which aid the separation of target speech and competing talkers (Beijen et al., 2008; Mok et al., 2006; 2007; 2010), as discussed in section 3.2. Case A's improved speech recognition in noise scores in the S0N0 and S0NHA listening conditions are at least in part due to the additional information provided via their contralateral HA.

Although the improvement in Case A's sentence recognition scores was consistent with our fifth hypothesis, their pattern of results was somewhat inconsistent with those of previous studies (Beijen et al., 2010; Mok et al., 2007). Consistent with previous studies, Case A scored lowest in the S0NCI condition (see *Figure 6.13*), the poor quality of their residual hearing possibly restricting their use of information presented to the non-implanted ear, making them more reliant upon the partially masked information available via their CI (Mok et al., 2007). Unexpectedly, Case A scored considerably higher in the S0N0 listening condition than in the S0NHA listening condition in both the CI-alone and BMS conditions (see *Figure 6.13*). A shift in the noise source from 0° azimuth (S0N0 condition) to the side of the non-implanted ear (S0NHA condition) should improve the SNR at the side of the implanted ear due to the head-shadow effect (Mok et al., 2007). However, it is possible that Case A was unable to benefit from the head-shadow effect to the same degree as other implant recipients due to their small head circumference. Alternatively, it is possible that the noise presented to the side of the hearing aid may have been distracting, rather than useful, resulting in poorer speech discrimination.

7.1.3 Speech Recognition Summary

Overall, our results provided some evidence in support of our first hypothesis. Although there was no significant difference between the mean CNC word scores of the eBM and CI-only groups, the proportion of high-scoring eBM children was significantly greater than the proportion of high-scoring CI-only children for this task (p = 0.038). However, this result should be interpreted with caution, as all of the eBM participants had ADRO pre-programmed into their MAPs, which may have given them an additional advantage over their CI-only counterparts.

Consistent with our second hypothesis, we found no significant difference between the sentence recognition in quiet scores of the CI-only, HA-only and eBM groups. Contrary to our third hypothesis, we found no significant difference between the sentence recognition in noise scores of the CI-only and the HA-only or eBM groups. Ceiling effects were at least in part responsible for this result. Our findings support those of Gifford et al. (2008), and we advocate for the development of a more difficult sentence recognition test for the future assessment of children using a CI and/or HAs. Case A's results were partially consistent with our fifth hypothesis, with considerable bimodal benefit being demonstrated for three of the four HINT listening conditions.

7.2 Pitch Ranking Task

7.2.1 The Performance of Children with Bilateral Acoustic Hearing

The PRT used in the present study has previously been used with NH adults (Looi et al., 2004, 2008b; Sucher & McDermott, 2007), but not children, hence 15 NH children, aged-matched to participants in the hearing-impaired groups were assessed using the PRT. The

NH group obtained mean scores of 96.9%, 94.6% and 88.8% correct on the 1, ½ and ¼ octave subtests respectively. These results are somewhat inconsistent with those of nine NH adults from Looi et al. (2004), who scored at ceiling levels on the ½ octave subtest. In addition, unlike NH adults in Looi et al. (2008b), NH children scored significantly lower on the ¼ octave subtest than the 1 octave subtest (p = 0.002). Sucher & McDermott (2007) reported that NH adults with formal musical training scored significantly higher on the PRT than their untrained counterparts for ½ octave and semitone interval sizes. In the present study, the mean PRT scores of the NH group were moderately correlated with musical experience level (ρ = 0.676, p = 0.006; MEL). All six participants with mean PRT scores of < 92% correct were also those who had either attended only a few formal music lessons, or had no formal musical training. We suggest that differences between the music experience level of NH adults from previous studies and the NH children in the present study probably contributed to the slightly poorer performance of the latter for smaller interval sizes (≤ ¼ octave). Despite this the overall performance of our NH group was consistent results from Stalinski et al. (2008) (see section 2.2).

The HA-only group had mean scores of 95.4%, 85.4% and 79.11% correct on the 1, ½ and ¼ octave subtests respectively. A brief review of the literature (see Table 7.2) indicates that HA users with bilateral severe to profound SNHL are likely to score lower than their NH counterparts, for at least smaller interval sizes (≤ ¼ of an octave). Consistent with this, we found no significant difference between the scores of the HA-only and NH groups for the 1 octave and ½ octave subtests. Unexpectedly, there were also no significant differences between the scores of the HA-only (M = 79.11%) and NH groups (M = 88.79%) for the ¼ octave subtest. However, there were also no significant differences between the scores of the HA-only, CI-only (M = 67.45%) and eBM (M = 63.99%) groups on the ¼ octave subtest, indicative of the wide range of scores for the HA-only group (SD = 19.74% points; see *Figure 6.7*). This high variability may be in part related to the wide range of hearing thresholds of participant in the HA-only group.

Study	Group	(*n*)	PRT Subtest (Percentage Correct)					
			1 Octave		½ Octave		¼ Octave	
			M	*SD*	*M*	*SD*	*M*	*SD*
Looi et al. (2004)	NH	9			~100.0*		~96.0*	
Sucher et al. (2007)	NH	10			89.0	14.7		
Looi et al. (2008a)	HA-only	9	84.0	12.2	72.0	12.0	66.0	10.1
Looi et al. (2008b)	NH	10	>95.0$^{\psi}$		>95.0$^{\psi}$		>95.0$^{\psi}$	
Looi et al. (2008b)	HA-only	15	90.2	7.6	83.72	8.0	74.7	10.2

Table 7.2: Summary of PRT scores for NH adults and adult HA users from selected studies.
*Approximate scores only, as numerical values were not available.
$^{\psi}$Exact scores were not reported, however scores for all tests were >95.0% correct.

It has been established that cochlear hearing loss results in reduced frequency selectivity through increased auditory filter bandwidths (B. C. J. Moore & Peters, 1992). All of the HA-only participants in the present study had mean PTAs $\geq$ 40 - 50 dBHL, and may have had auditory filters more than twice as wide as those in NH individuals (B. C. J. Moore, 1996). Wider auditory filters reduce the ability of listeners to resolve the lower harmonics of complex sounds, impairing their ability to isolate the F0 and impairing their pitch perception (Arehart, 1994; Bernstein & Oxenham, 2006b). We propose that significant differences would have been observed with a larger HA-only group size and for the testing of smaller interval sizes (i.e. < ¼ of an octave). HA users in the present study had considerably higher speech perception scores (*M* = 95.6% HINT sentences correct) than adult HA users assessed with the PRT in previous studies (Looi et al., 2008a, 2008b) (*M* = 41.5% and 39.6% City University of New York sentences correct respectively), and are likely to have had considerably better residual hearing function than their adult counterparts. The complexity of speech recognition materials may also have played a role, the CUNY test reportedly being more difficult. Consistent with this, on average the child HA-only users scored slightly higher than adult HA-only users from Looi et al. (2008a, 2008b) on all three PRT subtests (see *Figure 7.1*).

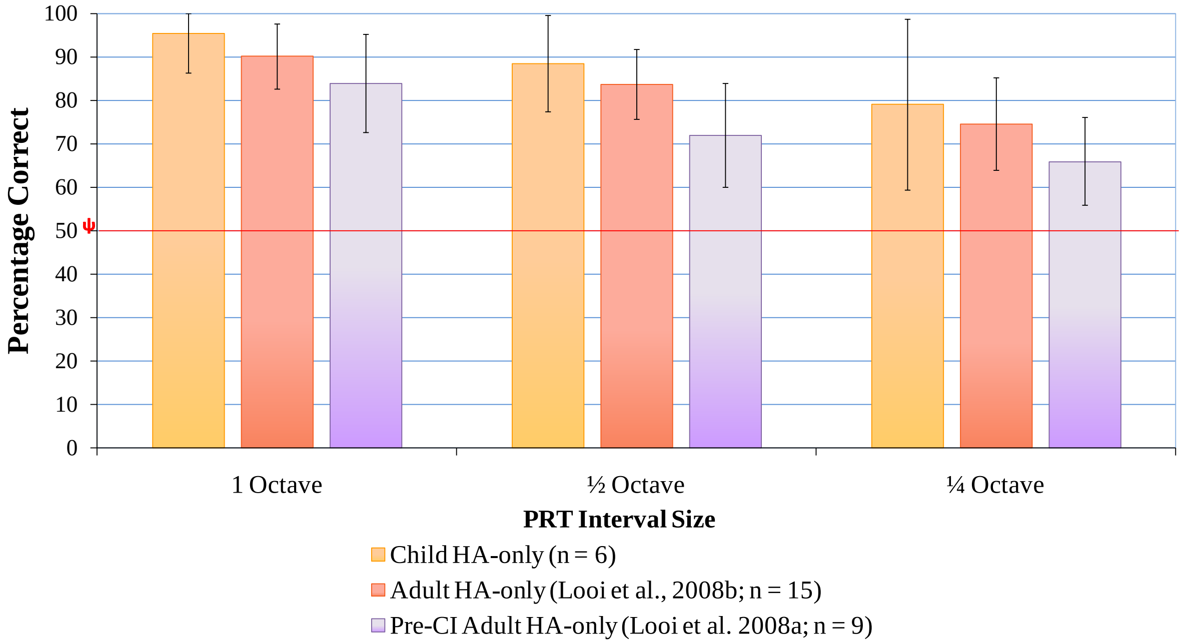

Figure 7.1: **PRT scores for HA users from the present study and Looi et al. (2008a, 2008b).**
ψIndicates the level of chance performance.

7.2.2 The Performance of Children using Electric-only Stimulation

The CI-only group had mean scores of 83.3%, 77.6% and 67.45% correct on the 1, ½ and ¼ octave subtests respectively. Overall, the PRT scores of the CI-only group were considerably higher than those of adult CI-only users from previous studies (Looi et al., 2008a, 2008b; Sucher & McDermott, 2007) (see *Figure 7.2*). In addition, unlike their adult counterparts, child CI-users scored above chance levels on the ¼ octave subtest ($p < 0.001$). It is important to note that adults were tested using both '/a/' and '/i/' sung vowels, while children were only assessed using '/a/'. However, as adult's scores were higher on average for the '/i/' vowel this factor can be excluded as a reason for the better performance of child CI-only users relative to their adult counterparts. Adult CI-only users also ranked the pitch of male-sung stimuli more accurately than female-sung stimuli (Looi et al., 2008a, 2008b), whereas we found no significant stimulus-gender difference in scores for children in the CI-only and eBM groups. Higher cortical plasticity may have enabled child CI users to more effectively adapt to electrical stimulation than their adult counterparts, allowing them to more effectively utilise the pitch cues provided via their CI. Differences in the distribution of SGNs in congenitally deafened children and postlingually deafened adults may also play a role. Studies using adult temporal bones have demonstrated a persistent, progressive deterioration in the size of the SGN population in the basal region of the cochlea (Incesulu & Nadol, 1998; Nadol & Eddington, 2006; Schuknecht & Gacek, 1993; Zimmermann et al., 1995). In contrast, Miura and colleagues (2002) found the pattern of SGN loss was more uniform across 50 pathological and 13 normal child cochleae, and that the size of the SGN population remained stable over the first decade of life. A larger, more evenly distributed SGN population may have allowed the child CI users in the present study to more accurately discriminate directional changes in the pattern of electrode activation across the array, improving the accuracy of pitch ranking judgements. Despite this, the pitch information provided by current CIs is still not sufficient to allow for the accurate discrimination of two closely-spaced musical notes in children.

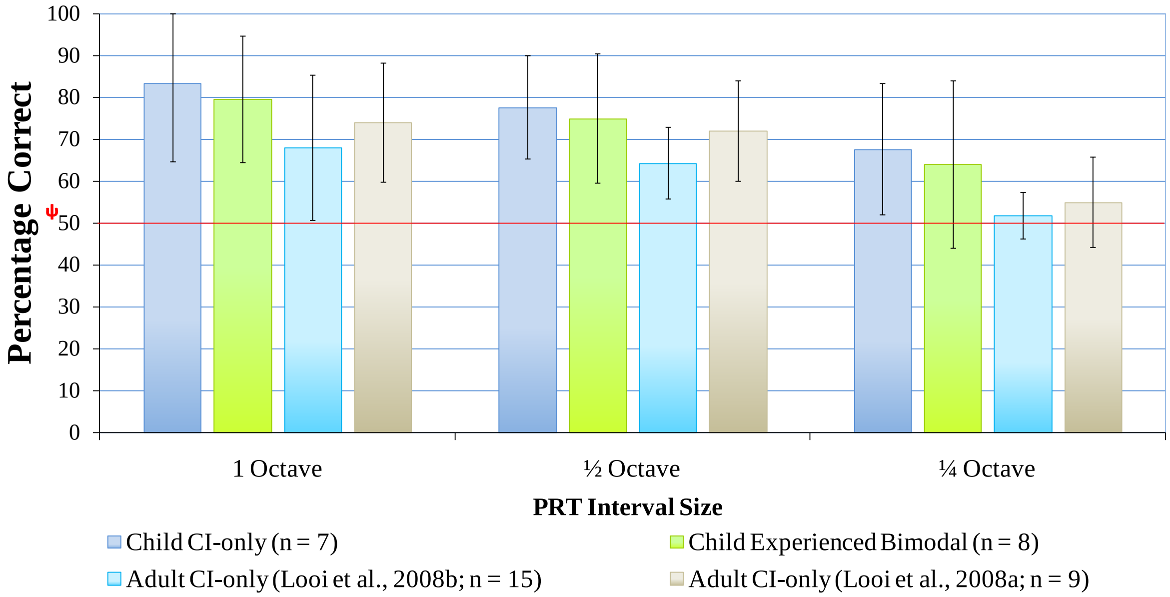

Figure 7.2: **PRT results for CI-users from the present study and Looi et al. (2008a, 2008b).** ψIndicates the level of chance performance.

7.2.3 Comparing Bilateral Acoustic and Electric-only Stimulation

Overall, participants with bilateral acoustic hearing (NH and HA-only groups) outperformed CI users (CI-only and eBM groups; see *Figure 6.5*). As expected, the CI-only group scored significantly lower than the NH group on all three PRT subtests (p < 0.001), consistent with the results of previous studies (Looi et al., 2004, 2008b; Sucher & McDermott, 2007). The CI-only group also scored significantly lower than the HA-only group on the 1 (p = 0.035) and ½ octave subtests ($p = 0.026$). This is partially consistent with the results of Looi et al. (2008b) who reported that adult HA users with bilateral severe-profound hearing loss outperformed 15 unilateral CI users on the 1, ½ and ¼ octave subtests of the PRT. Unlike Looi et al. (2008b), there were no significant differences between the scores of the HA-only and CI-only groups on the ¼ octave subtest. This is due to the combined effects of the higher performance of the CI-only children relative to their adult counterparts (see section 7.2.2), and the wide distribution of scores on the ¼ octave subtest for HA-only children (see *Figure 6.7*).

As discussed in section 2.1.2, accurate pitch perception requires that the listener extract information regarding the F0 from a complex acoustic signal. In both acoustic and electric hearing this information may be extracted by; (1) resolving the individual harmonics in a signal (place coding), and/or (2) extracting information regarding the F0 from the temporal output of auditory filters or CI bandpass filters (temporal coding).

In acoustic hearing, place coding for complex sounds involves the resolution of individual low-order harmonics by narrow-bandwidth auditory filters. These harmonics appear as individual peaks in the basilar membrane excitation pattern which can be compared with pre-formed “harmonic templates” to determine the F0. Place coding in CIs is considerably more limited (see section 2.3.2). Briefly, CI filterbanks are comprised of a small number of relatively wide bandpass filters that may not fully resolve low-order harmonics, making it difficult for CI users to determine the harmonic frequencies and make reliable pitch judgements. Even if individual harmonics are resolved, the user may only be able to determine which filter (or pair of filters) the harmonic falls into as this would result in the activation of the corresponding electrode(s). While there is some evidence that CI users are able to use place cues to determine the position of puretones within a filterband or pair of filterbands (Pretorius & Hanekom, 2008), this may not be true for the harmonics of complex sounds. A recent study by Laneau et al. (2004) found that following the removal of temporal pitch cues, adult CI users were unable to rank the F0 of pairs of synthetic vowels, even for

F0 differences as large as 1.7 octaves, highlighting the importance of temporal pitch cues in electric hearing, represented in the firing pattern of auditory neurons. In electric hearing (ACE and SPEAK strategies) the temporal envelope of the input signal is used to modulate the amplitude of a train of balanced-biphasic pulses. Changes in the pulse train amplitude provide information regarding the stimulus pitch. The salience of temporal pitch cues is affected by a variety of variables, discussed in detail in section 2.3.3, however the net result of these factors is the average CI user is unable to accurately discriminate the pitch of sounds with F0s above middle C (261.63 Hz) (Kong et al., 2009; Looi, 2008; McKay et al., 1994, 1995; Zeng, 2002).

Additionally, even if a CI-user is able to accurately perceive both place and temporal pitch cues, they may place different weightings on each, depending upon their salience and availability at the time, or cues may also provide conflicting information. For example, changes in the direction of the formant frequencies of sung vowels are not necessarily reflective of changes in the direction of the F0 (McDermott, 2004). It is possible that the pattern of electrode stimulation may shift apically due to a downward shift in the direction of the formant frequencies for a pair of notes that are ascending in pitch. At the same time, temporal pitch cues would represent an increase in the F0 through an increase in the amplitude-modulation rate. Overall, this pattern of activity would result in a pitch reversal for listeners attending to place cues. Alternatively, for sung vowels whose F0 exceeds the users' upper limit for using temporal pitch cues, the F0 difference between the two notes in a stimulus pair may not have been sufficiently large to result in a perceptible change in the place of stimulation.

In summary, the pitch information provided to CI users contains only crude representations of the pitch cues present in the original acoustic signal. Even if a CI user is able to perceive the place and temporal cues provided for a given sound these cues may provide conflicting information and/or the user may place different weightings on each type of cue, potentially limiting the accuracy of their pitch ranking judgements. In contrast, acoustic hearing uses a more accurate and robust coding system for pitch cues that enables a high level of performance, even with the reduced frequency resolution of a severe sensorineural hearing loss. These factors may account for the performance gap between the CI-only/eBM and NH/HA-only groups evident in the present study.

7.2.4 Comparing Bimodal and Electric-only Stimulation

The mean scores of the eBM group were 79.6%, 75.0% and 64.0% correct on the 1, ½ and ¼ octave subtests. Contrary to our fourth hypothesis, we found no significant differences between the scores of the eBM and CI-only groups on all three PRT subtests (see *Figure 6.5*). Numerous authors have suggested that the provision of more reliable F0-related and Temporal Fine Structure (TFS) information via acoustic residual hearing in BMS and EAS results in improved speech perception in quiet and noise through improved pitch perception (J. E. Chang et al., 2006; Dorman et al., 2008; Gfeller et al., 2006; 2007; Kong & Carlyon, 2007; Kong et al., 2004; Qin & Oxenham, 2005). A range of studies assessing the pitch perception abilities of adult BMS and EAS users in regards to melody recognition have consistently reported significantly higher scores when participants used electric and acoustic stimulation together, than electric stimulation alone (Dorman et al., 2008; Gfeller et al., 2006; Kong et al., 2004; Sucher & McDermott, 2009).

However, only one study has investigated the pitch perception abilities of children using BMS. Sucher (2007) reported no significant difference between the CI-alone and BMS scores of a group of experienced BMS users (n = 7) on the tonal subtest of the PMMA; a pitch discrimination task. However, as discussed in section 2.4, it was possible that the poor residual hearing levels of participants in Sucher's study may have limited their ability to utilise acoustic pitch cues (see *Figure 7.3*). Consistent with this El Fata et al. (2009) reported that a group of adult BMS users with similar unaided thresholds showed no significant bimodal benefit on a task of melody recognition (Group II, *Figure 7.3*).

Poor residual hearing is not likely to be solely responsible for the similar PRT performance of the eBM and CI-only groups of the present study. The mean low-frequency PTA of the eBM group was an average of 21.9 dBHL better than participants in Sucher (2007) and group II of El Fata et al. (2009), and is more comparable with the mean low-frequency PTAs of adult users of BMS from group I of El Fata et al. (2009) and Kong et al. (2004), who demonstrated significant bimodal benefit on tasks of melody recognition (see *Figure 7.3*). In addition, a moderate negative correlation was found between better-ear low-frequency PTA and mean PRT performance (ρ = -0.678, p = 0.011) in the present study, indicating that lower (better) low-frequency hearing thresholds were associated with higher PRT scores. As we did not test eBM participants using their HA in isolation, we were unable to determine the role that acoustic residual hearing played in their PRT performance. We recommend that future research examine the PRT performance of the implanted and non-implanted ear simultaneously and in isolation.

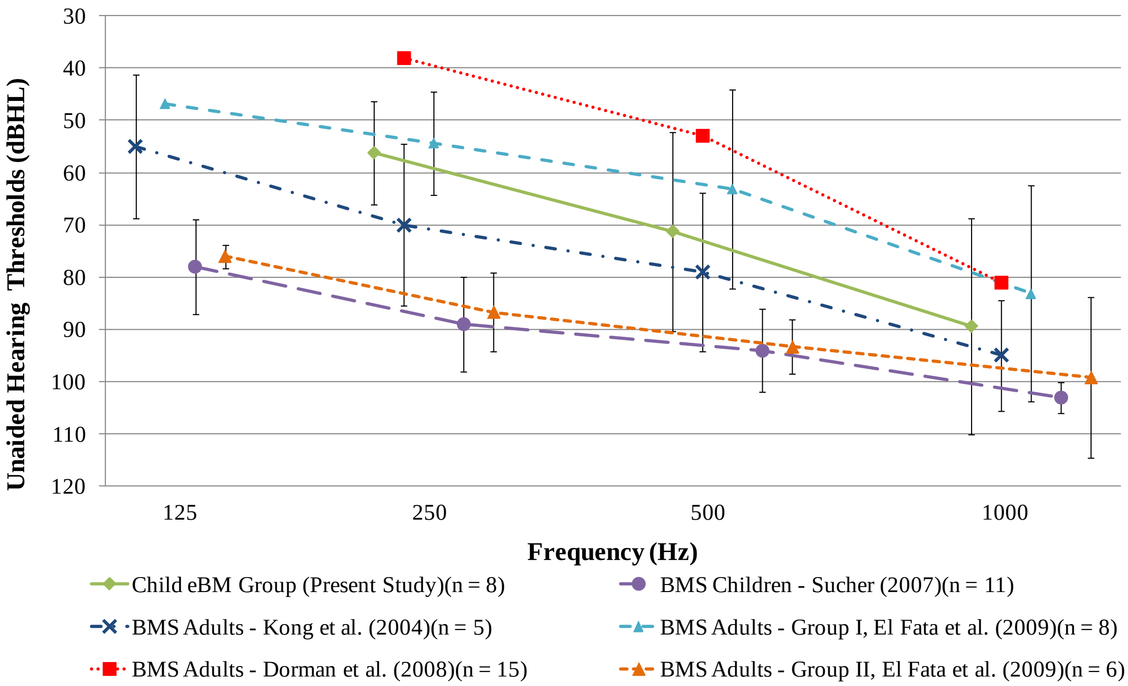

Figure 7.3: **Mean low-frequency unaided hearing thresholds of participants involved in studies investigating the melody recognition abilities of users of BMS.**

A potential confound in the results of our study is that participants in the eBM group were significantly younger (M = 9.24 years) than those in the CI-only group (M = 12.92 years).

NH children are capable of ranking pitch at an adult level by age 8 years of age (Stalinski et al., 2008). Longitudinal studies of pitch perception in hearing-impaired children have yet to be conducted, however given the poor salience of pitch cues available via a CI (as discussed in sections 2.3.2 through 2.3.4) and the limited residual hearing function of their non-implanted ear, it is possible that the pitch discrimination skills of the eBM group were not as fully developed as those of the older CI-only group. Such differences may have obscured any significant benefits that may have been obtained through the use of a contralateral HA. In support of this, a strong correlation was found between the chronological age of participants in the eBM group and their mean PRT scores ($\rho = 0.714$, $p = 0.036$; see *Figure 6.11*). As all of the participants in the CI-only and HA-only groups were over 10 years of age, and only 2 of the 15 NH participants were under 8 years of age we were unable to conduct similar correlations for the CI-only, HA-only and NH groups. The possibility of delayed development of the pitch ranking abilities of child BMS users should be investigated in future research involving a greater number of musically untrained CI-only, HA-only, eBM and NH listeners between 6 and 12 years of age.

However, it is also possible that the majority of the eBM group were simply unable to benefit from the pitch information provided by their non-implanted ear due to impaired central auditory development. Studies investigating the pitch perception abilities of postlingually deafened adult BMS users and NH adults listening through BMS simulations have consistently reported significant advantages for bimodal over electric-only stimulation, but no significant difference between BMS and HA-only scores (Kong & Carlyon, 2007; Kong et al., 2004; Sucher & McDermott, 2009). This suggests that postlingually deafened adult BMS users may be largely reliant upon pitch information arriving via the non-implanted ear. However, prelingually deafened children in the eBM group of the present study performed at levels similar to their CI-only peers, indicating that they may have been relying on the limited pitch information provided via their implants. A similar pattern is evident in the results of studies examining the role of the head shadow effect in BMS. Postlingually deafened adults are able to use the head shadow effect to improve speech recognition in noise regardless of whether their CI or HA has the better SNR (Mok et al., 2006). In contrast, prelingually deafened child users of BMS are unable to utilise the head shadow effect to improve speech recognition in noise when the SNR is better at the HA ear (Mok et al., 2007, 2010). This suggests that unlike their postlingually deafened counterparts, prelingually deafened child users of BMS may be less able to utilise the acoustic signal presented to them for speech recognition. It is possible that the quality of the signal provided via the non-implanted ear was insufficient for the normal maturation of central auditory pattern recognition systems and tonotopic maps in prelingually deafened children. Thus although children may receive additional information via a HA in their non-implanted ear, they may be less able to utilise this information relative to their postlingually deafened adult counterparts, making them more reliant upon information from their CI as a result.

If this is the case, then we might expect postlingually deafened BMS users who did not require implantation until later on in childhood to outperform their prelingually deafened peers, at least on tasks of pitch perception, and possibly also in certain speech recognition in noise conditions scenarios where their HA has a better SNR than their CI. Unfortunately, due to the high number of ceiling-level results for the HINT sentence task, further analysis of the eBM groups speech recognition in noise scores was not possible. However, as pitch discrimination skills mature around age 8 years, we might expect users of BMS who were implanted later than this to perform as well as HA-only users on the PRT. Participant D009 meet this criterion, was diagnosed with a progressive, moderately-severe sloping to profound bilateral SNHL at age 39 months, and was implanted at 12 years of age. Consistent with our prediction, D009 was the only eBM participant to score at levels comparable with those of HA-only users, with mean scores of 92.7%, 96.87% and 96.87% correct on 1, ½ and ¼ octave subtests respectively. It is possible that prolonged exposure to acoustic pitch information during periods critical for the development and refinement of tonotopic maps in the central auditory nervous system allowed D009 to more effectively utilise the acoustic information provided via their HA.

However, it is also possible that D009's hearing loss may not have been prelingual, especially given the late age at diagnosis and the underlying eitology: a recessive genetic mutation in the GJB2 gene coding for connexin 26. Mutations in this gene can result in a wide range of phenotypes ranging from mild to profound hearing loss depending upon the genotype (Liu et al., 2005). Unfortunately, the type, locus and severity of the mutation in D009 was not specified in SCIC records. In addition, it is possible that D009's deafness may not have been present at birth (Orzan & Murgia, 2006). A recent study by Norris et al. (2006) highlighted the cases of nine children with GJB2 mutations who passed newborn hearing screening and were later diagnosed with varying degrees of hearing loss, some as late as 60 months of age. Given D009's relatively late age at diagnosis it is possible that their hearing function was considerably better during early life. However, pre-diagnosis records for D009 were not on file at the SCIC, as the family had emigrated to Australia. Further research is required to determine whether age at implantation has an effect on the pitch perception abilities of eBM users.

Another major difference between the majority of the eBM participants and D009 is that the latter had 7 years of formal piano tuition, the majority of which took place prior implantation. In contrast the majority of the eBM group had no formal musical training, and had received their cochlear implants before 5 years of age (*M* = 4.87 years excluding D009). Musical training has been shown to result in the more faithful and robust encoding of linguistic pitch information at both the level of the brainstem and subcortical levels (Nikjeh, Lister, & Frisch, 2009; Wong, Skoe, Russo, Dees, & Kraus, 2007). In addition, the experience-dependent refinement of tonotopic precision in the auditory cortex, and multi-modal cortical regions has been well demonstrated (see E. F. Chang, Bao, Imaizumi, Schreiner, & Merzenich, 2005 for a review). It is likely that D009's extensive musical training contributed to the maturation of tonotopic maps in the central auditory nervous system. Future research should also investigate whether pre- and/or post-implantation musical training can be used to enhance the pitch perception of CI users.

It is also possible that the acoustic pitch information provided via the HA on most of the eBM users was not audible, or that they preferentially relied upon more audible information from their CIs when making pitch ranking judgements, limiting their potential performance. Alternatively, their HA and CI may have provided conflicting information regarding the direction of the pitch change. Such conflicts may have resulted in increased confusion and reduced accuracy when making pitch ranking decisions, resulting in poorer overall scores. Binaural interference was reported in 5 BMS users (children and adults) in Luntz et al. (2005), participants scoring lower using BMS than a CI-alone on a task of speech recognition in the presence of spatially coincident noise (Ching et al., 2001). Similarly, the assessment of children in CI-only, HA-only and eBM conditions will be necessary to determine whether binaural interference impairs pitch ranking in BMS.

Finally, eitology of hearing loss may have limited the pitch ranking accuracy of the eBM group. Unlike the CI-only group, the majority of children in the eBM group were born premature and/or experienced hypoxia or anoxia at birth (see Table 5.2 and Table 5.3). Miura et al. (2002) reported that of 50 pathological child cochleae, significantly larger SGN populations were found in children who had contracted congenital infectious diseases than those with inherited genetic disorders or anomalies and those who suffered from asphyxia. Given that the majority of the eBM group have both inherited genetic disorders and experienced asphyxia at birth it is possible that they had considerably smaller SGN populations than the CI-only participants, potentially limiting their sensitivity to directional changes in stimulation across the electrode array, although it would be difficult to assess any such limitations.

7.2.4.1 Bimodal Case Study: Case A

The results of our case study support the final part of our fifth hypothesis: that the addition of an optimally fitted HA in the non-implanted ear of a child CI user will result improved pitch perception. Using their CI-alone, Case A performed at levels similar to those of the CI-only group with mean scores of 81.3%, 77.2% and 64.1% correct on the 1, ½ and ¼ octave subtests respectively. With the addition of a contralateral HA, Case A's pitch ranking accuracy improved across all three subtests, their overall mean score increasing from 71.4% to 83.0% correct. Case As SDRs were considerably greater than those of the CI-only group for the 1 and ½ octave subtests for male-sung stimuli (see *Figure 6.17*), indicating that the addition of a contralateral HA resulted in improved pitch ranking on these subtests. Learning effects probably accounted for any improvements in the pitch ranking accuracy of female-sung stimuli for all three interval sizes, and male-sung stimuli for the ¼ octave interval size. These results are consistent with those involving adult BMS users and NH participants listening to simulations of BMS which indicate that BMS allows for an improved perception of pitch relative to a CI-alone (Dorman et al., 2008; Dorman, Spahr, Loizou, Dana, & Schmidt, 2005; Kong et al., 2004; Sucher & McDermott, 2009).

7.2.5 The Role of Other Perceptual Dimensions in Pitch Ranking Decisions

It should be noted that although pre-task instruction and training was provided to children regarding 'the concept of pitch,' it is impossible to verify conclusively if pitch ranking judgements were made solely on that one dimension. Participants may have used other cues, such as timbral differences, in their decision making process, particularly if pitch cues were not salient (Looi et al., 2008b). Numerous researchers have suggested that variations in the place of stimulation may affect timbre more than pitch for CI users (McDermott, 2004; McDermott & McKay, 1997; B. C. J. Moore & Carlyon, 2005; Pijl, 1997), and studies involving NH listeners have also found interactions between the perceptual dimensions of pitch and timbre, particularly for those with little musical experience (Beal, 1985; Crowder, 1989; Pitt & Crowder, 1992).

7.3 Questionnaire Ratings

7.3.1 Between-group Comparisons

The Parental Perceptions of Listening Device Performance Questionnaire (PPLDPQ) asked parents to rate their child's performance across five subcategories: device usage; speech in quiet; speech in noise; environmental awareness, and; music and fine structure, using a five-point rating scale. The combined ratings of the parents of children in the CI-only group (*M* = 3.85, *SD* = 0.80) were higher than those of the eBM (*M* = 3.66, *SD* = 0.6) and HA-only groups (*M* = 3.10, *SD* = 0.90), however any differences in overall ratings were not statistically significant.

Parental ratings were highest for the device usage subdomain, which addressed issues such as daily usage and loudness discomfort. There were no significant differences in mean ratings between the three groups for this subdomain. Mean parental ratings on the music and fine structure subdomain were moderately positive. There were no significant differences between ratings for the CI-only (*M* = 3.69), HA-only (*M* = 3.72) and eBM groups (*M* = 3.96) for this subdomain. Responses indicated that most parents believed that their children's listening devices allowed them to recognise the voices of immediate family members (overall *M* = 4.60), however "recognising familiar voices" over the telephone was rated as being a greater challenge for all groups (overall *M* = 3.07), in part be due to the restricted frequency response and variable quality and/or volume of calls made via traditional telephone systems. Parents of CI-only users agreed with the statement that their children were "less likely to recognise songs other children know" (*M* = 2.64) more than parents of BMS users (*M* = 3.25) and HA-only users (*M* = 3.50). The perception that CI-only users are less able to recognise familiar melodies than their NH peers is consistent with the results of melody recognition studies (Mitani et al., 2007; Nakata et al., 2005; Vongpaisal et al., 2004, 2006, 2009). Interestingly, the parents of participants in the eBM group gave higher ratings for questions relating to enjoyment of music (*M* = 4.31) than parents of children in the CI-only (*M* = 3.44) and HA-only (*M* = 3.67) groups. In all cases, parent's ratings of their child were consistent with the child's own response to the question "Do you enjoy listening to music?" to which all of the CI-only users (9/9), most HA-only users (5/6) and most users of BMS (5/8) responded "yes." Overall our results are consistent with Gfeller et al. (1998) who reported that despite the inherent limitations of CI technology in regards to music, a large proportion of child recipients enjoy listening and participating in music related activities, of both a formal and informal nature. Ratings on the environmental awareness subdomain were significantly lower for the HA-only group (M = 2.6) than the CI-only (M = 3.9, p = 0.016) and eBM groups (M = 3.8, p = 0.024). It is possible that poorer audibility of high frequency sounds of HA-only users compared to CI-only users may limit their perception of environmental sounds.

Overall, parents of bilateral HA users rated their child's speech perception outcomes in quiet (M = 2.65) and noise (M = 2.67) lower than parents of unilateral CI users (M = 3.75 in quiet, 3.51 in noise) and eBM users (M = 3.64 in quiet, 3.23 in noise). Across these two subdomains the HA-only group received the lowest rating for 17 of the 19 questions with 18 mean ratings of $\leq$ 3.00. Questions with the lowest ratings across all groups included: holding conversations with either a familiar an unfamiliar talker using the telephone; and understanding dinner conversation when at a restaurant for noisy situations. CNC word list scores were moderately and strongly correlated with ratings for speech in quiet (ρ = 0.490, p = 0.024) and noise (ρ = 0.545, p = 0.024), indicating that parents rankings are generally consistent with their child's fundamental speech recognition abilities.

7.3.2 New Bimodal Case Study (Case A)

When asked directly, the parents of Case A noticed little difference in their child's overall performance following the addition of a contralateral HA. Mean ratings were very positive for both the CI-only and BMS conditions. The only notable difference was an improvement in the understanding of dinner conversations in a noisy restaurant, which was given a rating of '1' in the CI-only condition, and a rating of '4' in the bimodal condition, suggesting some degree of improved speech recognition perception in noisy environments when using BMS. Overall, the mean rating for the speech in noise category improved markedly from 3.7 to 4.4 consistent with their improved HINT sentence recognition scores in quiet for the BMS condition (see section 7.1.2.2).

7.4 Study Limitations

Due to the small number of participants in each group, the results of the present study may not generalise to the wider population of child CI-only, HA-only and eBM users. In addition, the small number of participants has made it difficult to observe and measure possible age-related trends in relation to PRT performance.

The analyses of our results have been complicated further by the significant difference in the mean age of the CI-only (M = 12.92 years) and eBM groups (M = 9.24 years; p = 0.036) and the possibility of an experience-dependent delay in the maturation of pitch perception skills in these groups as discussed in section 7.2.4. Such a delay may have impacted on the validity of comparisons between the eBM group and other participant groups.

A secondary consequence of the low-response rates was that our intention to directly investigate bimodal benefit by fitting a HA to existing CI-only recipients who had residual hearing in their non-implanted ear was not possible, and was restricted to a single case study. In addition, due to time and resource limitations we were unable to assess eBM participants using their CI-alone and HA-alone and are unable to determine the contribution of each device to their overall bimodal test scores.

As discussed in section 7.1.1.1, while the majority of the CI-only group used an ESPrit 3G processor, all of the eBM group used the more advanced Freedom speech processor with ADRO preset in the MAPs of all normal listening programmes. Unfortunately, restrictions in our ethical approval prevented MAP alteration. ADRO may have provided the eBM group with additional advantages for word recognition, potentially confounding comparisons between these two groups.

It should also be noted that as the CI-users in the present study were implanted with Nucleus 24 implant systems, using the SPEAK or ACE speech processing strategies. Hence, the results of this study may not generalise to users of other implant systems or speech processing strategies.

7.5 Future Research

As discussed in section 1.5, the sentence recognition results of the present study are consistent with those of Gifford et al. (2008) indicating that the administration of the HINT sentence task using fixed SNRs is likely to overestimate the real-world sentence recognition performance of CI and HA users. We advocate the development of a New Zealand version of a more difficult sentence recognition test. To ensure a high level of flexibility, we recommend that target sentences be recorded using both male and female talkers, and include speech-weighted noise, multi-talker babble, and single-talker maskers (same talkers as target speech, and different male & female talkers). Such a test could be used for assessing a wide range of performance factors for both research and everyday clinical purposes. For the moment we recommend the HINT sentence task be administered in its intended adaptive format (Gifford et al., 2008; Luxford et al., 2001).

As discussed in section 7.2.4, the present study has highlighted a range of potential factors that may impact on the pitch perception abilities of children using BMS. We suggest that future studies assess the pitch perception performance of children using BMS in CI-alone, HA-alone and BMS conditions in order to determine the contribution of each ear to overall performance. We also suggest recommend that the effects of pre- and/or post-implantation musical training on the pitch perception abilities of children using a unilateral CI or BMS be investigated. Finally an assessment of the pitch ranking abilities of adult users of BMS is necessary in order to discover whether prelingually deafened child users of BMS reach the same levels of performance as their postlingually deafened adult counterparts.

8 Conclusions

The purpose of the present study was to compare the performance of children using a unilateral CI, bilateral HAs and BMS on tasks of speech recognition in quiet and noise, and a pitch ranking task. We found limited evidence in support of the hypothesis that BMS allows for improved word recognition in quiet compared to a CI-alone. We found no evidence in support of the hypothesis that BMS allows for improved sentence recognition in noise and quiet compared to a CI-alone with the majority of participants scoring at ceiling levels across all four listening conditions. We are in agreement with Gifford et al. (2008), who recommended against the use of the HINT sentences test as a test of speech recognition in quiet, and at fixed SNRs. We advocate the development of a New Zealand version of a more difficult speech recognition test for this purpose. Until this is available, we recommend that the HINT sentence lists be administered using an adaptive format according to the guidelines of the Luxford et al. (2001).

Overall, child CI-only and eBM users ranked pitch considerably more accurately than their postlingually deafened adult counterparts in Looi et al. (2008; 2008b). Greater cortical plasticity in children may have allowed them to more effectively adapt to electrical stimulation than their adult counterparts. Alternatively, the more uniform distribution of SGNs seen in child cochleae may have enabled them to more accurately perceive changes in the direction of the pattern of electrical stimulation across the array than their adult counterparts. However, like their adult counterparts, the child CI users in the present study did not reliably rank the pitch of two closely-spaced musical notes.

Our results provide limited evidence in support of the hypothesis that the additional pitch information provided via the contralateral HA of BMS users allows for improved pitch ranking compared to a CI-alone. Case A and one of the children in the eBM group were the only BMS users to exhibit any apparent bimodal benefit on the PRT. Establishing a performance history for the non-implanted ear of BMS users through additional clinical monitoring may be warranted in order to evaluate whether a child is obtaining significant bimodal benefit. Overall, our results indicate a need for further research into the contribution of the non-implanted ears of BMS users to pitch perception, and whether pre- and/or post-implantation musical training can improve pitch perception in users of BMS.

To listen to simulations illustrating the benefits of bimodal stimulation for music perception, created during this study, please visit '<u>thelisteningtree.wordpress.com</u>'

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Appendix I: Hearing Aid Optimisation

Each child's HA was optimised for use with their CI according to a protocol designed by Ching et al. (Gifford et al., 2008; Luxford et al., 2001) as discussed below. There are two parts to the optimisation process. Part A involves the determination of the best frequency-response settings (FRS) for understanding speech. Part B involves balancing the loudness of the HA to match that of the CI. All materials for this task are available at the National Acoustics Laboratory website (nal.gov.au).

I. Part A

Three programs with different FRSs were created in the HA programming software. These include an NAL-NL1 FRS, low-frequency boost FRS, and a low-frequency cut FRS. The low-frequency boost FRS provides a 6 dB/octave boost for the frequencies 250-2000Hz relative to the NAL FRS. The low-frequency cut settings provide a 6 dB/octave cut for the frequencies 250-2000Hz relative to the NAL FRS.

The stimulus used in the HA optimisation process was a digitally recorded audiovisual (AV) presentation of the HINT sentences in quiet. During stimuli presentation, the participant's CI was turned off, and they listened using their HA alone. The loudness of the different FRSs was first adjusted to ensure they are set at a comfortable level. Participants were instructed to watch the AV presentation and indicate whether the volume of the sound was comfortable by pointing to the appropriate picture on a pictorial loudness scale (see Figure). The overall gain of the HA was then adjusted where necessary. This task was performed using the NAL FRS and both alternative FRSs until the participant reported that each response level was of a comfortable loudness.

Figure I.I: Pictorial loudness scale used in loudness balancing protocol.

Next the loudness of the alternative FRSs were compared and matched to the NAL FRS using a paired comparisons task. Participants watched the AV presentation; only this time the audiologist switched between the NAL prescription (A) and one of the alternative FRSs (B). Participants were instructed to compare A to B, and indicate whether B was louder, the same, or softer than A using a pictorial loudness scale (see figure 3). The overall gain of the HA was adjusted where necessary until the participant reported that both alternative FRSs were equally as loud as the NAL prescription.

Figure I.II: Pictorial loudness comparison scale for loudness balancing protocol.

Participants were then asked to judge which response provided them with the best understanding of the AV speech presentation. Alternative FRSs were presented in pairs in a randomised order until a clear preference for one was indicated according to the paired comparisons scoring sheet (see Figure).

II. Part B

The details of the loudness balancing protocol varied, depending on the hearing aid used. The procedure for loudness balancing a single channel linear hearing aid with an automatic gain control (AGCi) to a CI is described below to convey basic principles. The CI was first switched on, and then any user-adjustable automatic processing features which may alter the loudness of the signal (in this case the AGCi of the HA) are switched off. A continuous AV presentation of the HINT sentences in quiet was presented at a level of 55 dBSPL from a loudspeaker was positioned at 0° azimuth and at a distance of 1.0m from the participant. The CI and HA were switched on and off in an alternating fashion. Participants were instructed to remember the loudness of the CI and compare it to the loudness of their HA. The overall gain of the hearing aid was adjusted until the participant rated the loudness of the HA to be the same as that of the CI, using the pictorial loudness scale in where necessary (see Figure). The AGCi was then turned back on and post-filter compression enabled. The volume of the HINT sentence presentation was increased to 80 dBSPL, and the compression threshold of the HA was adjusted until the participant rated the loudness of speech in the HA to be the same as that of the CI using a loudness comparison scale (see Figure). With both the CI and HA switched on, the intensity of the HINT presentation was decreased to 65 dBSPL, and the participant was asked whether the loudness of both devices is comfortable using the loudness judgement scale (see figure 4). If gain adjustments required an increase in the maximum power output (MPO) of the aid, the level was checked using an Audioscan Verifit VF-1 Real Ear Analyser to ensure loud sounds did not cause significant discomfort for the participant.

Stage 1. Compare the NAL response with each alternative 4 times.
Record the number of times a frequency response is preferred:

	NAL	+6dB/oct	-6dB/oct
A			
B			
TOTAL			

Excluding NAL, are any of the totals 2 or more?

☐ No. This evaluation is complete. The NAL response is the preferred response.

☐ Yes. Retain responses having a score of 2 or more.
Discard other responses and cross out the discared response on this score sheet.

Stage 2. Compare the NAL response with each remaining alternative 4 times.
Record the number of times a frequency response is preferred:

	NAL	+6dB/oct	-6dB/oct
A			
B			
TOTAL			
Combined TOTAL: Stages 1 + 2			

Excluding NAL, are any of the combined totals (1+2) 6 or more?

☐ No. Evaluation is complete. The NAL response is the preferred response.

☐ Yes. Is that total 7 or more? ☐ No. Retain the response having a total of 6.
☐ Yes. That is the selected response.

Stage 3. Compare the NAL response with the remaining alternative 4 times.
Record the number of times a frequency response is preferred:

	NAL	+6dB/oct	-6dB/oct
A			
B			
TOTAL			
Combined TOTAL: Stages 1 + 2+ 3			

Excluding NAL, are any of the combined totals (1+2+3) 10 or more?

☐ No. Evaluation is complete. The NAL response is the preferred response.

☐ Yes. That is the preferred response.
It is significantly better than the NAL response for speech intelligibility.

Figure I.III: Paired comparisons score sheet used in loudness balancing protocol.

Appendix II: Pitch Ranking Task Materials

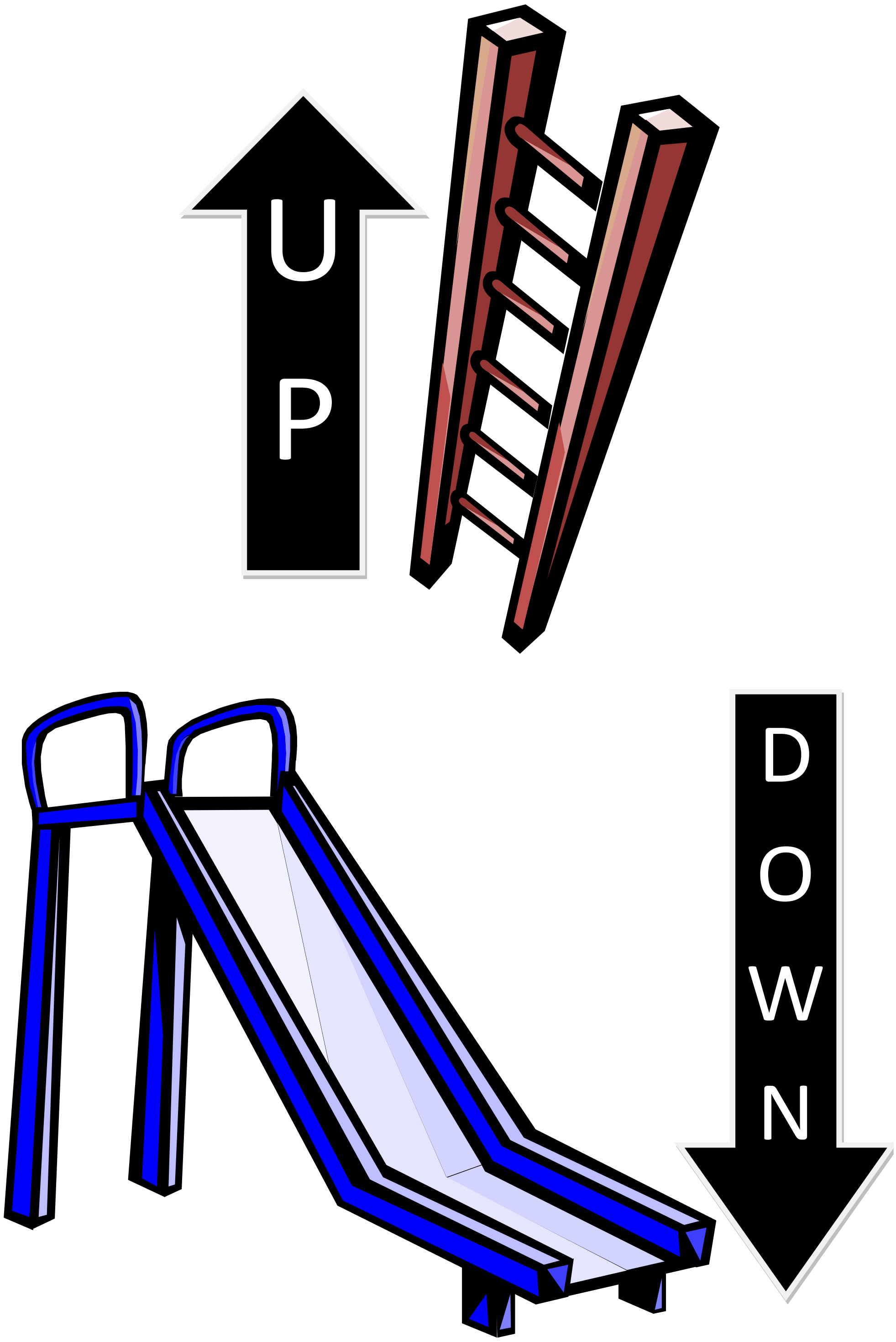

Figure II.I: Paired comparisons score sheet used in loudness balancing protocol Pictorial scale used to help children decide whether the pair of sung vowels went ‘up’ or ‘down’ in pitch.

Appendix III: Information Sheet for Audiologists (Group A)

The following information sheet was provided to the local audiologist of Group A candidates who agreed to participate in the study.

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

INFORMATION SHEET FOR PROFESSIONALS

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

BACKGROUND

Cochlear implants (CIs) provide a perception of hearing to over 400 New Zealanders with severe to profound sensorineural hearing loss. Many CI users are able to obtain good open-set speech perception in quiet, and report significant improvements in their quality of life. However, the information provided by a CI is significantly different to the acoustic input signal. In addition, most CI users in New Zealand have monaural hearing due to the high cost of/and lack of government funding for bilateral implantation. As a result, CI users experience difficulty understanding speech in noisy situations, localising environmental sounds, identifying the voices of individuals, and accurately perceiving music.

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of both pediatric and adult CI users who have residual hearing in that ear. This is known as electro-acoustic stimulation, or binaural bimodal stimulation (BBS). The quality of the acoustic signal provided by the hearing aid in conjunction with the provision of binaural input has the potential to provide CI users with significant performance gains for speech in noise understanding, voice identification, sound localisation, and music perception.

The purpose of this study is to determine the extent of any benefits provided by binaural bimodal stimulation (BBS) on speech and pitch perception in children with cochlear implants (CIs) who have residual hearing in their non-implanted ear.

In order to investigate this, four groups of children will be recruited: A - experienced CI users with residual hearing function in their non-implanted ear; B - experienced CI-only users; *C - experienced bilateral hearing aid (HA) users*; and D –experienced BBS (CI + HA) users.

Children in group A will be fitted with a HA in their non-implanted ear which will be worn for three weeks prior to optimisation for use with their CI. Their performance on tests of speech (in quiet and noise) and pitch perception will be assessed using when using their CI-only. At the same time their parent/caregiver will complete a questionnaire evaluating their perception of their child's performance using their CI alone. The child will then be required to use their CI and HA (BBS) together for a three month period. At the end of this period the tests of speech and pitch perception will be re-administered with the child using a BBS setup. Their parent/caregiver will complete a version of the questionnaire assessing their views of their child's performance using BBS.

Children in *groups B, C and D* will be assessed on the same tests of speech and pitch perception as group A with their parent/caregiver completing a questionnaire examining their views on their child's performance using their hearing device(s). After a three month interval, children in groups B, C and D will be re-assessed on the same tests of speech and pitch perception in order to account for any learning effects.

It is hypothesised that; (i) That the addition of an optimally fitted HA in the non-implanted ear of children using a CI will result in better performance in tests of speech in noise and pitch perception, but there will be no difference for performance on tests of speech performance in quiet; (ii) That children who use a CI will score higher than children using only a HA(s) on speech perception tests (both in quiet and noise), however children with HAs will score better on the tests of pitch perception.

GROUP A CANDIDACY CRITERIA

INCLUSION CRITERIA

- full time CI users, with at least 1 year experience with their CI
- have not used a HA in their non-implanted ear post-implantation
- have aidable hearing thresholds in contralateral ear (e.g. severe level of hearing loss at frequencies 1kHz & below)
- be willing to use a HA in contralateral ear full-time for at least 3 months
- no additional impairments
- spoken English as first language
- prelingual onset of hearing loss
- Age 5 years or older
- Educated in an oral/aural learning environment

GROUP A PROCEDURE

GROUP A

Children in group A would be required to attend 4 appointments. The first two appointments are required for the fitting of a HA to the child's non-implanted ear. The parent/caregiver(s) of children living in Christchurch may choose to have an audiologist from the University of Canterbury Speech and Hearing Clinic fit the HA, otherwise the appointment will be with their local audiologist.

The first session will involve measurement of the hearing levels in the child's non-implanted ear. Records at the Southern Cochlear Implant Programme have indicated that the participant referred had some aidable residual hearing in their non-implanted ear, however, this may have deteriorated over time. Where aidable hearing remains the most appropriate aid should be selected and an earmould manufactured. Where no aidable hearing remains the child the primary researcher should be notified as the child may be offered a place in Group B.

The second appointment involves fitting of the aid. The researcher will provide you with a copy of a closed-format questionnaire assessing parent/caregiver perceptions of their child's performance when using their CI, to be filled in by the attending parent/caregiver and returned at the end of the appointment. When setting up the device, please note the NAL-RP and NAL-NL1 prescriptions have been verified for used in bimodal fittings in children. A hearing aid usage diary will be provided for the parents to fill out. Ideally the child should be wearing the aid at least eight hours a day by the end of the three week trial period.

The third and fourth appointments will take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch.

The third appointment will be approximately two hours long and be broken into two parts. Children will firstly be assessed used tests of speech and pitch perception using their CI-only. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes (i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. These tests will take approximately 90 minutes.

After the child's HA will be optimised for use with their CI. This involves a paired comparisons procedure for selection of a preset frequency response that maximises speech intelligibility. Clinicians will be asked to provide an electronic copy of the hearing aid fitting data prior to appointment three so that alternate frequency responses can be established prior to testing. Adjustments will then be made to equate the loudness of the child's HA with their CI. No changes to the MAP settings on the child's CI will be made and the details of changes made to the HA will be forwarded to their audiologist. Once optimisation has been completed the child will need to use both the HA in conjunction with the CI for three months.

At the end of this three month period the child would need to attend a final appointment, again held at the University of Canterbury Speech and Hearing Clinic in Christchurch. In this appointment the tests of speech and pitch perception performed in appointment three will be re-administered with the child using their CI and HA together. The child will be asked to fill in a similar questionnaire as in appointment three, however this one will be to assess their views and experiences in relation to your child's performance when using the CI and HA together.

GROUP A TIMETABLE

The timetable for the study is relatively fixed due to the 3 month space between testing of all groups.

Testing will be interrupted for two weeks in July and again for one week (TBA) in late September/October while the researcher is in Sydney testing participants for Group D.

JUNE 18 Recruitment begins

JUNE 23 Begin hearing aid fittings

JULY 02 Recruitment Ends

JULY 06 Primary Researcher in Sydney

JULY 18 Complete aid fitting

JULY 21 Primary Researcher returns to NZ

JULY 22 Third session begins

AUG 10 Third session ends

EARLY OCT Primary Researcher in Sydney

MID OCT Fourth session begins

NOV 02 Fourth session ends

Group A Timetable

DAY	MONTH	M	T	W	R	F	S	S
	JUNE	09	10	11	12	13	14	15
18 - 02	Recruitment	16	17	18	19	20	21	22
23	Aid Fitting Start	23	24	25	26	27	28	29
	JULY	30	01	02	03	04	05	06
06 - 21	Sydney	07	08	09	10	11	12	13
18	Aid Fitting End	14	15	16	17	18	19	20
22	Third Session Start	21	22	23	24	25	26	27
	AUGUST	28	29	30	31	01	02	03
10	Third Session End	04	05	06	07	08	09	10
	Paul Unavailable	11	12	13	14	15	16	17
		18	19	20	21	22	23	24
		25	26	27	28	29	30	31
	SEPTEMBER	01	02	03	04	05	06	07
		08	09	10	11	12	13	14
		15	16	17	18	19	20	21
		22	23	24	25	26	27	28
	OCTOBER	29	30	01	02	03	04	05
28	Sydney	06	07	08	09	10	11	12
6	Fourth Session Start	13	14	15	16	17	18	19
	NOVEMBER	20	21	22	23	24	25	26
2	Fourth Session End	27	28	29	30	31	01	02

BENEFITS & RISKS

Participants in Group A may benefit from improved performance perceiving speech in noise and localising sounds in their environment when listening with both the CI and HA. They will also be able to keep the HA after the study has finished, should they choose to continue using it.

It is not expected that the participants in groups B, C or D will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your local Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

Children in Group A may initially find the sound from the HA unusual, or different, however it is not expected that this would negatively impact on their speech perception ability. However, there is a small risk that some individuals may have greater difficulty hearing with a CI and HA than a CI-only. Parents/ caregivers will be counseled regarding this possibility. Should they find that their child's ability to perceive speech, or their day-to-day functioning is significantly impaired, they are free to discontinue using the HA and/or withdraw from the study at any time, without penalty or impact on their child's audiological care. Also, the child and/or parent/caregiver(s) may find it more time consuming having to manage 2 devices.

CONTACT INFORMATION

Concerns and enquiries should first be directed to the principal researcher, Chris Radford. Any queries or concerns regarding the personal rights of the parent/caregiver(s) of participants, or the rights of participants in this study should be directed to an independent Health and Disability Advocate.

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Appendix IV: Information Sheet for AODCs

The following information sheet was provided to the Advisers on Deaf Education (AODCs), Christchurch branch, prior to recruitment.

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

INFORMATION SHEET FOR PROFESSIONALS

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

BACKGROUND

Cochlear implants (CIs) provide a perception of hearing to over 400 New Zealanders with severe to profound sensorineural hearing loss. Many CI users are able to obtain good open-set speech perception in quiet, and report significant improvements in their quality of life. However, the information provided by a CI is significantly different to the acoustic input signal. In addition, most CI users in New Zealand have monaural hearing due to the high cost of/and lack of government funding for bilateral implantation. As a result, CI users experience difficulty understanding speech in noisy situations, localising environmental sounds, identifying the voices of individuals, and accurately perceiving music.

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of both pediatric and adult CI users who have residual hearing in that ear. This is known as electro-acoustic stimulation, or binaural bimodal stimulation (BBS). The quality of the acoustic signal provided by the hearing aid in conjunction with the provision of binaural input has the potential to provide CI users with significant performance gains for speech in noise understanding, voice identification, sound localisation, and music perception.

The purpose of this study is to determine the extent of any benefits provided by binaural bimodal stimulation (BBS) on speech and pitch perception in children with cochlear implants (CIs) who have residual hearing in their non-implanted ear.

In order to investigate this, four groups of children will be recruited: A - experienced CI users with residual hearing function in their non-implanted ear; B - experienced CI-only users; *C - experienced bilateral hearing aid (HA) users*; and D –experienced BBS (CI + HA) users.

Children in group A will be fitted with a HA in their non-implanted ear which will be worn for three weeks prior to optimisation for use with their CI. Their performance on tests of speech (in quiet and noise) and pitch perception will be assessed using when using their CI-only. At the same time their parent/caregiver will complete a questionnaire evaluating their perception of their child's performance using their CI alone. The child will then be required to use their CI and HA (BBS) together for a three month period. At the end of this period the tests of speech and pitch perception will be re-administered with the child using a BBS setup. Their parent/caregiver will complete a version of the questionnaire assessing their views of their child's performance using BBS.

Children in *groups B, C and D* will be assessed on the same tests of speech and pitch perception as group A with their parent/caregiver completing a questionnaire examining their views on their child's performance using their hearing device(s). After a three month interval, children in groups B, C and D will be re-assessed on the same tests of speech and pitch perception in order to account for any learning effects.

It is hypothesised that; (i) That the addition of an optimally fitted HA in the non-implanted ear of children using a CI will result in better performance in tests of speech in noise and pitch perception, but there will be no difference for performance on tests of speech performance in quiet; (ii) That children who use a CI will score higher than children using only a HA(s) on speech perception tests (both in quiet and noise), however children with HAs will score better on the tests of pitch perception.

GROUP C CANDIDACY CRITERIA

INCLUSION CRITERIA

- 10 - 15 children who have used bilateral HAs for at least 1 year
- Bilateral moderately-severe to profound sensorineural hearing loss between 1 and 4 kHz
- Age 6 years or older (listening age)
- Use spoken English as their first language
- Educated in an oral/aural learning environment

EXCLUSION CRITERIA

- No greater than a ±20 dB HL asymmetry between ears (puretone average).
- Mixed or conductive hearing loss
- History of rapid hearing loss progression (significant changes within three months)
- History of fluctuating (±15 dB HL) sensorineural hearing loss
- Recent history of untreated chronic middle ear infection (within past 18 months)
- Additional significant impairments

GROUP C TIMETABLE

The timetable for study is relatively fixed due to the 3 month space between testing of all groups. However due to delays in ethical approval our timelines are slightly off. Nonetheless, testing is available the week following the beginning of recruitment to all potential participants who express an early interest in the project.

Testing will be interrupted for two weeks in July and again for one week (TBA) in late September/October while the researcher is in Sydney testing participants for Group D.

JUNE 18	Recruitment begins
JUNE 23	First session begins
JULY 13	Recruitment ends
AUGUST 03	First session ends
SEPTEMBER 15	Second session begins
NOVEMBER 02	Second session ends

DAY	MONTH	M	T	W	R	F	S	S
	JUNE	9	10	11	12	13	14	15
18	Recruitment Start	16	17	18	19	20	21	22
23	Session 1 Start	23	24	25	26	27	28	29
	JULY	30	1	2	3	4	5	06
06 - 21	Sydney	7	8	9	10	11	12	13
13	Recruitment End	14	15	16	17	18	19	20
		21	22	23	24	25	26	27
	AUGUST	28	29	30	31	1	2	3
10	Session 1 End	4	5	6	7	8	9	10
		11	12	13	14	15	16	17
		18	19	20	21	22	23	24
		25	26	27	28	29	30	31
	SEPTEMBER	1	2	3	4	5	6	7
15	Session 2 Start	8	9	10	11	12	13	14
		15	16	17	18	19	20	21
		22	23	24	25	26	27	28
	OCTOBER	29	30	1	2	3	4	5
TBA	Sydney	6	7	8	9	10	11	12
		13	14	15	16	17	18	19
	NOVEMBER	20	21	22	23	24	25	26
2	Session 2 End	27	28	29	30	31	1	2

PARENTAL COMMITTMENTS

Participants will commit to two taking part in two testing sessions. Each session will involve tests of speech and pitch perception and last around 90 minutes long. Each testing session will last approximately 90 minutes and will be three approximately three months apart. Each session will involve tests of speech and pitch perception. Participants will be reimbursed for direct travel costs to and from appointments within Christchurch.

BENEFITS & RISKS

It is not expected that the participants in groups C will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your their Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

The risks associated with the research are not different from those that would be expected in everyday use of the CIs or HAs, or attending a hearing test at an audiology clinic. For all of the testing, the stimuli will be presented at everyday, comfortable levels. Children will be under the care of a qualified audiologist who will monitor their hearing sensitivity and provide appropriate counseling and support.

CONTACT INFORMATION

Concerns and enquiries should first be directed to the principal researcher, Chris Radford. Any queries or concerns regarding the personal rights of the parent/caregiver(s) of participants, or the rights of participants in this study should be directed to an independent Health and Disability Advocate.

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Appendix V: Participants Statement of Rights

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Participant's Statement of Rights

Any person who is asked to participate in a research study within this department, or who is requested to consent on behalf of another, has the right to be:

1. Informed of the nature and purpose of the study.

2. Given an explanation which they understand, of the procedures to be used in the study.

3. Given a description of discomforts and risks reasonably expected from the study, if applicable.

4. Given an explanation of any benefits (or lack of) that may reasonably be expected from the study, if applicable.

5. Advised of appropriate, alternative procedures, or programs that might be advantageous to the subject, and their relative risks and benefits, if applicable.

6. Given an opportunity to ask questions concerning the study or the procedures involved.

7. Informed that their consent to participate may be withdrawn at any time, and that they may discontinue participation in the study without prejudice.

8. Given a copy of the signed and dated written consent form when one is required.

9. Given the opportunity to decide to consent or not to consent to participate in the study without the intervention of any element of force, fraud, deceit, duress, coercion or undue influence.

Appendix VI: Group A Information Pack

The information pack for Group A participants included the following:

- A copy of the participant statement of rights (see appendix VI);
- A Group A invitation letter;
- A copy of the information sheet for parents/caregivers of children in Group A;
- A copy of the information sheet for children in Group A and/or a copy of the information sheet for adolescents in Group A, and;
- A New Zealand consent form for participants in Group A

Also included were a pre-paid return envelope and a return slip (illustrated below) for those who preferred not to take part in the study.

I DO NOT WANT MY CHILD TO PARTICIPATE IN THIS STUDY

IF YOU DO NOT WISH FOR YOUR CHILD TO PARTICIPATE IN THIS STUDY PLEASE RETURN THIS SLIP IN THE ATTACHED PRE-PAID ENVELOPE TO THE FOLLOWING ADDRESS BY WEDNESDAY JULY 02, 2008. PLEASE DO NOT HESITATE TO CONTACT US IF YOU HAVE ANY QUESTIONS REGARDING THE STUDY. THANK YOU FOR YOUR CONSIDERATION.

Chris Radford, c/o Department of Communication Disorders,

Dear parents/caregivers,

We write to you today to inform you about a research study being conducted at the University of Canterbury that may be of interest to you as a parent of a child who uses a cochlear implant (CI).

CIs currently provide a perception of hearing to over four hundred New Zealanders with severe to profound hearing loss. Advances in implant technology mean that CIs are now capable of providing the majority of user's with good open-set speech perception.

Current practice in New Zealand is to implant only one ear. However the brain is designed to work best with input from both ears. A lack of input from both ears results in significant difficulties in the lives of CI users including difficulty locating sounds within their environments, and a relatively poor ability to understand speech in noisy or reverberant environments.

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of CI users who have enough hearing left in that ear. This setup is known as bimodal hearing - the HA provides acoustic stimulation, whereas the CI provides electrical stimulation. The acoustic stimulation provided by the HA may provide the brain with additional information that is not typically conveyed by a CI. This information can potentially improve a CI user's performance in more complex listening tasks, such as perceiving speech in noise and listening to music.

A study investigating the effects of bimodal stimulation on the speech and pitch perception abilities of children with CIs is being conducted as part of a Master's Thesis at the University of Canterbury, in conjunction with the Southern Cochlear Implant Program (SCIP).

Records at the SCIP suggest that your child, may be a suitable candidate for a bimodal fitting. We write to you invite your child to participate as a member of GROUP A of our study.

Participation would involve 4 appointments. The first two appointments involve the fitting a HA to your child's non-implanted ear by your local audiologist. The following two appointments would occur at the University of Canterbury Speech and Hearing Clinic in Christchurch. The first of these would involve optimising the HA for use with the CI to ensure maximal benefit, and testing their performance on tests of speech and pitch perception using their CI only. Following this, we could ask your child to wear the HA in conjunction with their CI for 3 months. After this they would need to return to Christchurch to be reassessed on the same tests as the previous session, but this time using the HA and CI together.

Appointments can be organized outside of school hours, during the weekend and, where appropriate, in the evenings. Where feasible, for subjects residing outside Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch. Where participants reside outside the Canterbury region, a contribution will be made towards travel costs to/from Christchurch. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city.

More detail is provided in the attached information sheet, and we would be more than happy to answer any further questions that you may have. Our contact numbers are listed below. If you are able to assist us by allowing your child to participate in this study, please contact the primary researcher using the details below and return the included consent form in the pre-paid envelope by WEDNESDAY JULY 2ND. If you are unable to participate in this study, we would appreciate it if you could return the separate slip and return it to us in the enclosed envelope; this just allows us to keep a track of replies received for this study. Again, please do not hesitate to contact us if you need any more information on this study.

Thank you for your time and consideration.

Sincerely,

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THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

INFORMATION FOR PARENTS OF PARTICIPANTS IN RESEARCH

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

AIMS OF THE RESEARCH

The main aim of this study is to investigate whether the addition of a hearing aid (HA) can provide children with cochlear implants (CIs) with any additional benefits for perceiving speech and/or pitch. It will also compare whether there are differences between child users of a CI, and child users of HAs in their ability to perceive speech and/or pitch.

It is hoped that the results of this study will help inform clinical practice, and be used to lobby the Government and other funding bodies for increased funding for the cochlear implant program.

PARTICIPATION CRITERIA

Four groups of children will be involved:

GROUP A Children who have used a CI for at least 6 months, have aidable levels of hearing in their non-implanted ear, and are willing to trial a HA in that ear for 3 months;

GROUP B Children who have used a CI-only for 6 months or longer; and

GROUP C Children who have used HA(s)-only for 6 months or longer

GROUP D Children who have used a CI and HA together for 6 months or longer

Your child has been suggested as a potential candidate in the group on the attached invitation letter. Participation in this study in addition to any testing conducted as part of your local Cochlear Implant Program's audiological management, or normal audiological testing for group C. You are free to withdraw your child from this study at any time, without penalty nor affect on their current/future audiological care.

DESCRIPTION OF THE PROCEDURE

GROUP A

Children in group A would be required to attend 4 appointments. The first two appointments are required for the fitting of a HA to your child's non-implanted ear. The initial two appointments will be with your child's local audiologist. If you live in Christchurch you may also choose to have the aid fitted by an audiologist from the University of Canterbury Speech and Hearing Clinic.

The first two sessions should be around in 1 hour duration each. In the first session the audiologist will measure the hearing levels in your child's non-implanted ear, and select the most appropriate HA for your child in consultation with you. An earmould impression will then be taken and sent for earmould

manufacture. A second appointment will be held once the audiologist has received the HA and earmould (approximately 2 -3 weeks later). The HA will then be appropriately fitted to your child. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant) when using their CI. Appropriate counselling regarding the use and management of HAs will be provided at this appointment. Your child will then be required to wear the HA with their CI for approximately 2-3 weeks prior to the third appointment.

The third and fourth appointments will take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city.

The third appointment will be approximately two hours long and be broken into two parts. Your child will first be assessed on tests of speech and pitch perception when listening through their CI only. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes (i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. These tests will take approximately 90 minutes.

After this, your child's HA will be optimised for use with the CI. This involves making adjustments to the HA so that the loudness of each device is the same. Your child will need to make comparisons regarding the loudness of different speech materials (sentences) presented using an audiovisual presentation. No changes to the MAP settings on your child's CI will be made and any the details of changes made to the HA will be forwarded to their audiologist. Once optimisation has been completed your child will need to use both the HA in conjunction with the CI for three months.

At the end of this three month period your child would need to attend a final appointment, again held at the University of Canterbury Speech and Hearing Clinic in Christchurch. In this appointment the tests of speech and pitch perception performed in appointment three will be re-administered, however this time your child will be listening using both their CI and the HA. You will be asked to fill in a similar questionnaire as in appointment three, however this one will be to assess your views and experiences in relation to your child's performance when using the CI and HA together.

At the end of the study your child is welcome to keep the HA should you or your child wish, or you can return the HA if you prefer. There will be no charge for the HA.

GROUPS B AND C

Children in groups B and C would be required to attend two appointments, approximately three months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at University of Canterbury Speech and Hearing Clinic and be organised around travel into or around Christchurch wherever possible. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city. The first appointment will last approximately 90 minutes. In the first session your child will be assessed on tests of speech perception and pitch perception, when listening with their CI (Group B) or HAs (Group C). For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes

(i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant). The second appointment will last approximately 90 minutes. The same speech and pitch tests conducted in the first appointment will be re-administered. This is to check test-retest consistency in the results and to account for any improvements in performance for group A over the duration of the study.

GROUP D

Your child would be required to attend 2 appointments, approximately 3 months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at Sydney Cochlear Implant Centre and last approximately 90 minutes. In the sessions your child will be assessed on tests of speech perception and pitch perception, when listening with their CI+HA. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and in the presence of background noise. For the pitch test, they will be required to state whether two notes presented via a loudspeaker go up or down in pitch. In the second appointment these speech and pitch perception tests will be re-administered. This is to check test-retest consistency in the results. You would also be asked to complete a brief parental perspectives questionnaire regarding your child's performance with their CI+HA.

POSSIBLE BENEFIT

Participants in Group A may benefit from improved performance perceiving speech in noise and localising sounds in their environment when listening with both the CI and HA. They will also be able to keep the HA after the study has finished, should they choose to continue using it.

It is not expected that the participants in groups B, C or D will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your local Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

POSSIBLE RISKS

GROUP A

Children in Group A may initially find the sound from the HA unusual, or different, however it is not expected that this would negatively impact on their speech perception ability. However, there is a small risk that some individuals may have greater difficulty hearing with a CI and HA than a CI-only. Parents/ caregivers will be counseled regarding this possibility. Should you find that your child's ability to perceive speech, or their day-to-day functioning is significantly impaired, you are free to discontinue using the HA and/or withdraw from the study at any time, without penalty or impact on your child's audiological care.

Also, your child and/or you may find it more time consuming having to manage 2 devices. Appropriate counseling regarding device usage and maintenance will be provided by your audiologist at the second appointment, and you are welcome to contact the researcher should you have any concerns or questions regarding the fitting of the HA. You will also be able to contact the researcher at any time during the study period (e.g. during the 3 month CI with HA trial), if you have any concerns or questions.

GROUPS B, C AND D

For children in groups B, C, and D the risks associated with the research are not different from those that would be expected in everyday use of the CIs or HAs, or attending a hearing test at an audiology clinic. For all of the testing, the stimuli will be presented at everyday, comfortable levels. Your child will be under the care of a qualified audiologist who will monitor their hearing sensitivity and provide appropriate counseling and support. You will be able to contact the researcher at any time during the study period, if you have any concerns or questions.

COMPLETION OF THE STUDY

It is estimated that this study will be completed by 1st March 2009. Copies of your child's results for this study can be forwarded to your audiologist should you request. It is planned for the research results to be published in appropriate scientific or clinical journals, and the findings may also be presented at international and national conferences or seminars. No information which could lead to your child's identification will be included in any publications or presentations using the data obtained in this study. The Sydney Cochlear Implant Centre, Southern Cochlear Implant Program and Advisors on Deaf Children will be informed of any publications that arise from this study, the details of which can be provided to you if requested.

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

If you have any concerns in regards to any aspect of this research, you are encouraged to contact the principal researcher, Chris Radford.

Should you have any complaints please contact the Department of Communication Disorders, the University of Canterbury, or the supervisors for this project, Valerie Looi or Paul Peryman. f you have any queries or concerns regarding your personal rights, or the rights of your child as a participant in this study feel free to contact an independent Health and Disability Advocate.

CONTACT DETAILS

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CHRIS RADFORD, MASTERS OF AUDIOLOGY STUDENT

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HEALTH AND DISABILITY ADVOCATE SERVICES

PH: 0800 423 638 (Lower North Island) PH: 0800 377 766 (South Island)

FAX: 0800 2787 7678 (Nationwide) EMAIL: advocacy@hdc.org.nz (Nationwide)

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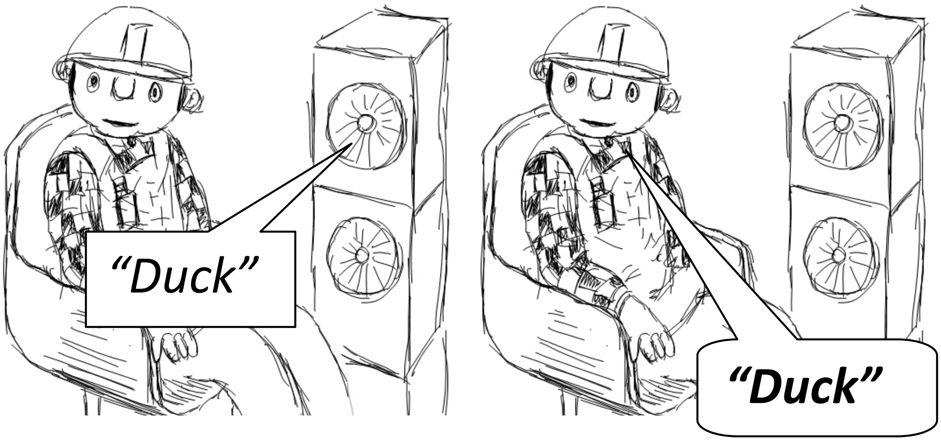
DEPARTMENT OF COMMUNICATION DISORDERS

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

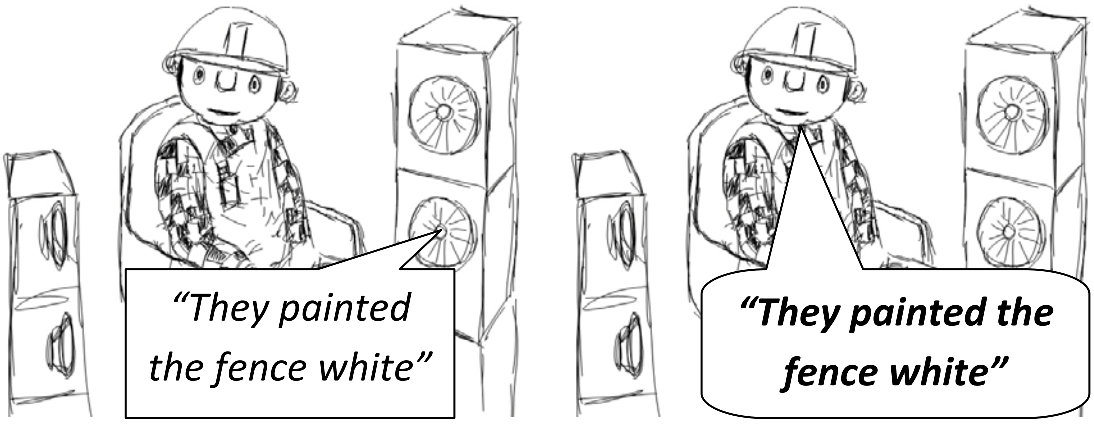
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~5-8

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

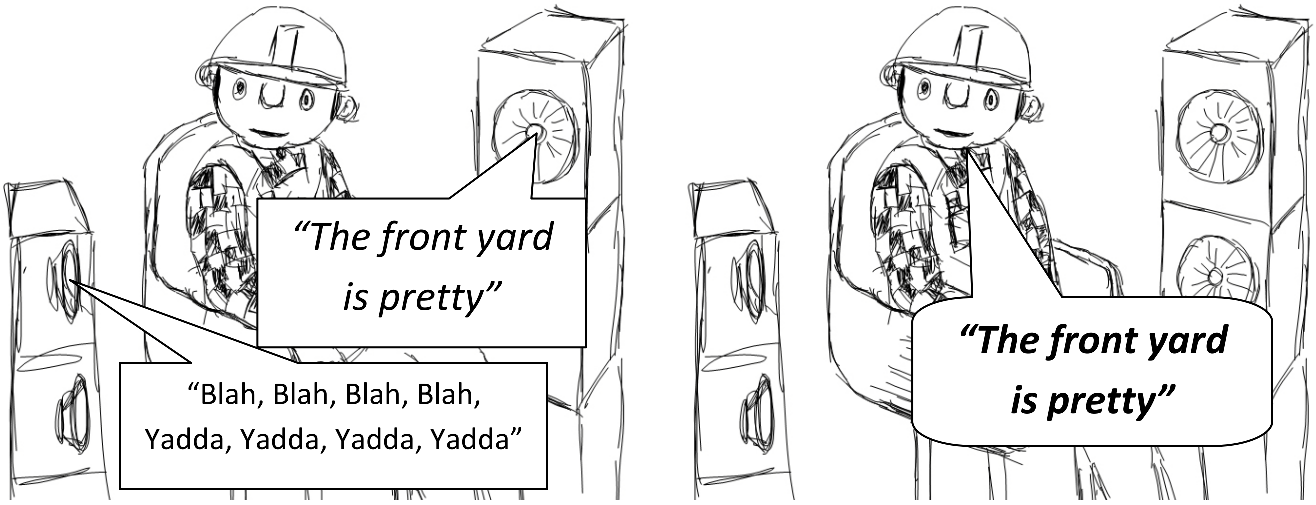
We invite you to take part in a listening game challenge as part of work at the University of Canterbury. To help prepare you for the games we want to give your cochlear implant a friend, a hearing aid, for your other ear. A hearing aid can work together with your implant, and may help you hear music better, and help you find your friends when they call you on the playground. We need you to train for the games by wearing your hearing aid whenever you use your cochlear implant. When you have finished your training you'll be ready to play our four listening games!



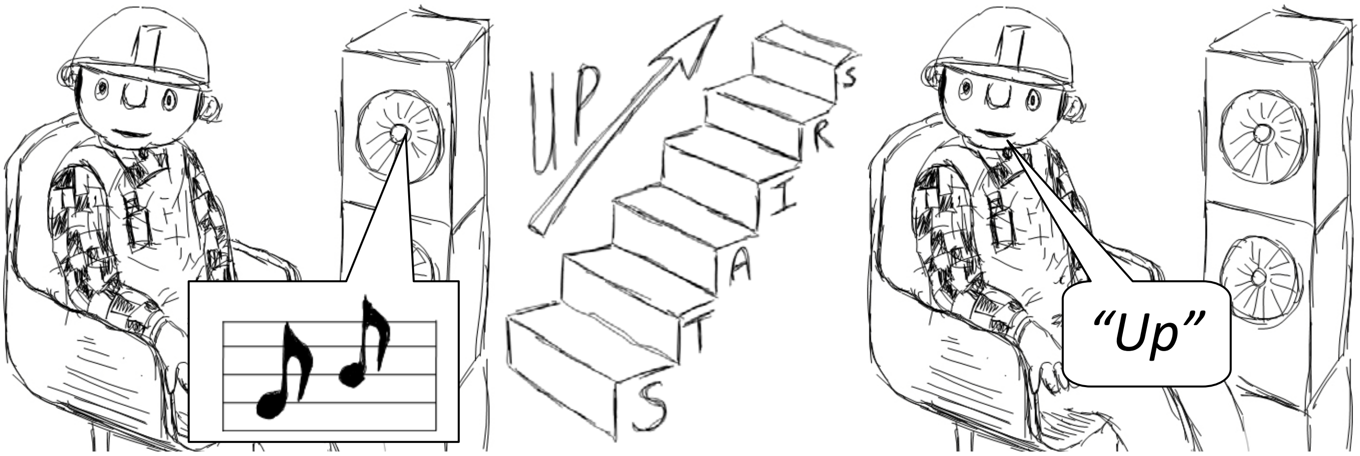
In the first game you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "duck" you say "duck." If you're not sure or don't know what the woman said, have a guess.



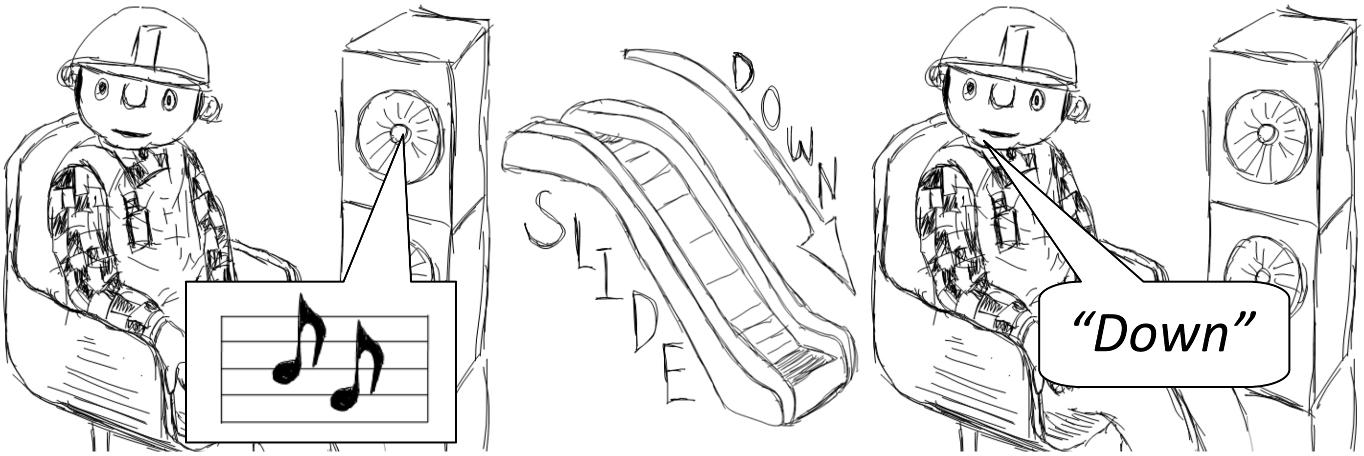
In the second game you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third game you'll hear a woman say a sentence over a loudspeaker like in the last game. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to the sentence the other woman is saying. So if she says "the front yard is pretty" you say "the front yard is pretty." If you're not sure or don't know what the woman said, have a guess.



In the fourth game you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes go up in pitch you say "up", or point to the picture of the stairs.



If the two notes go down in pitch you say "down", or point to a picture of a slide. This listening game will be played at three different levels. As you pass each level you'll be able to score more points.

If you live outside Christchurch you may even make a special trip just to come play these games with us! Good luck, we hope to see you soon!

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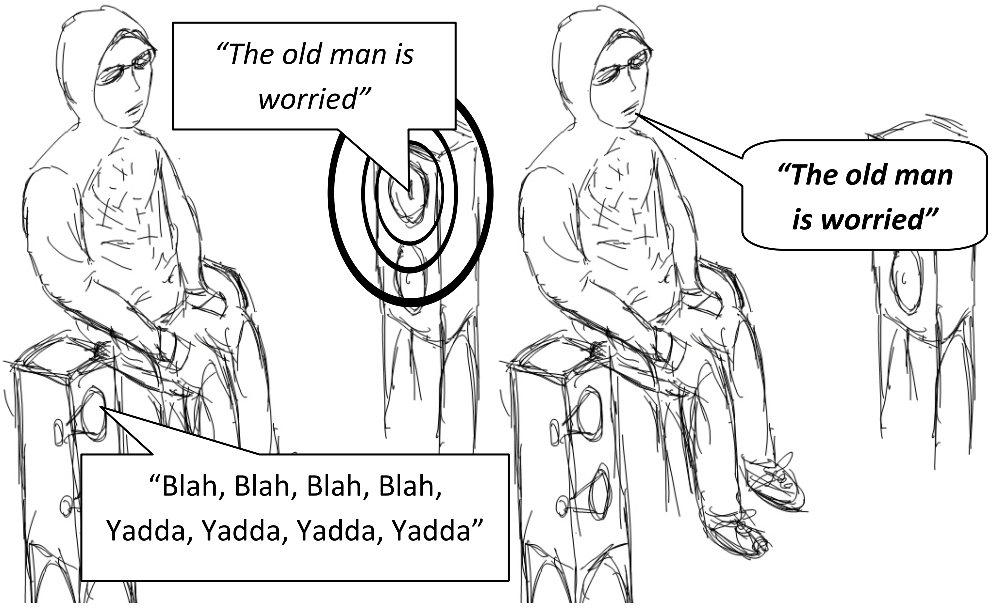
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~9-16

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

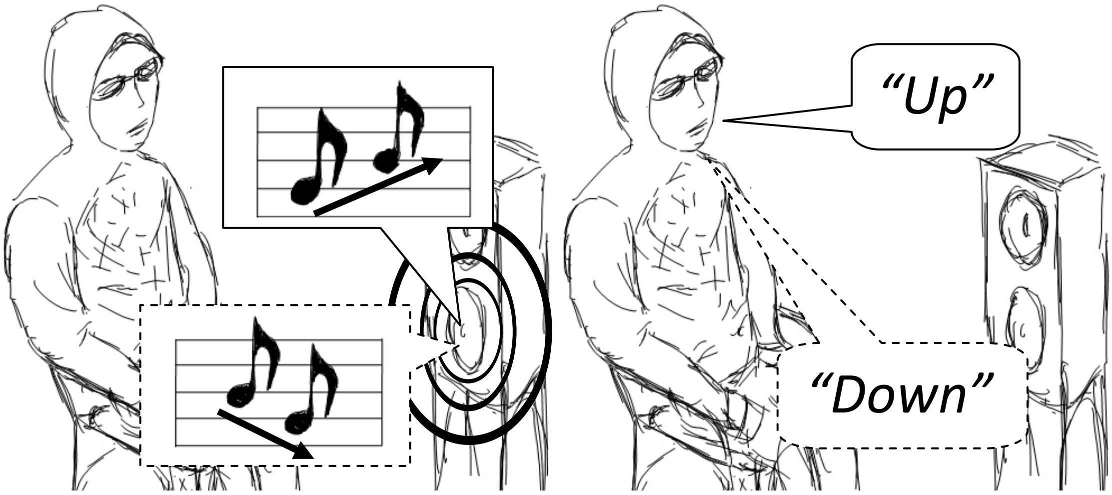
We invite you to take part in a series of listening challenges as part of research at the University of Canterbury. To help prepare you for these challenges we would like your local audiologist to fit a hearing aid (HA) to your non-implanted ear. A HA can work together with your cochlear implant (CI), and may improve the sound of music, and improve your ability to locate sounds in your environment, e.g. finding a ringing mobile phone in a messy room. Getting a HA to work well with your CI requires regular use of both devices together. We would need you to use the HA whenever you use your CI for a period of 4 months. There are two sets of four listening challenges. Your first challenges will takes place three weeks into your HA trial. In the first set of challenges you will be listening using your CI-only.

In the first challenge you'll hear a woman talking over a loudspeaker. She will say single words, for example 'boat' or 'car.' All you need to do is repeat what the woman says. So if the woman says "June" you will say "June." If you're not sure or don't know what the woman said, have a guess.

In the second challenge you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you'll say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third challenge you'll hear a woman say a sentence over a loudspeaker as in the previous task. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to what the other woman is saying. So if she says "the old man is worried" you say "the old man is worried." If you're not sure or don't know what the woman said, have a guess.



In the fourth challenge you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes rise in pitch you say "up." If the two notes go down in pitch you say "down." This challenge will increase in difficulty as you advance through the task.

At the end of this first set of challenges, we will attempt to provide you with the best sound possible by adjust the loudness of the HA so that it is balanced with the loudness of your CI. It is important you become used to wearing the HA fulltime for 3 weeks before balancing to give you enough time to adjust to the new sound and let us know what you think of the sound so we can accurately balance the two devices. We would then like you to wear your CI and HA together for three months.

At the end of the 3 months you will perform a second set of challenges that will test your listening abilities using your CI and HA working together to measure any improvement in performance compared with your CI-only performance.

All testing will take place at the University of Canterbury, in Christchurch, and will be organized around travel to the Southern Cochlear Implant Program wherever possible.

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UNIVERSITY OF CANTERBURY
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CHRISTCHURCH NEW ZEALAND

Consent Form for Participants in Research

PROJECT TITLE: THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

RESEARCHERS

	Christopher Radford	Valerie Looi	Paul Peryman
	Masters of Audiology Student	Lecturer in Audiology	Senior Audiologist
PH:	(03) 366 7001 ext: 4816	(03) 366 7001 ext: 3051	(03) 326 6009
EMAIL:	cjr120@student.canterbury.ac.nz	valerie.looi@canterbury.ac.nz	pperyman@vanasch.school.nz

DECLARATION

I have read and I understand the information sheet for participants taking part in the study designed to investigate the effect of bimodal stimulation on speech and pitch perception in children with cochlear implants dated 13/05/2008. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

I have had the opportunity to use whanau support or a friend to help me ask questions and understand the study.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child from the study at any time and this will in no way affect their future health care, continuing health care, academic progress and/ or employment.

I understand that researchers directly involved in this study may contact my child's audiologist and/or access their audiological files held at their audiology clinic.

I understand that the results of my child's tests are completely confidential, and no material which could identify them will be used in any reports on this study.

I have had the time to consider whether to take part.

I know who to contact if my child has any side effects to any of the procedures, or treatments involved in this study.

I ....(full name) hereby consent for my child

....(full name) to take part in this study

SIGNATURE.. DATE ....

CONTACT DETAILS OF PARTICIPANT

NAME: .... DATE OF BIRTH: ....

PARENT/CAREGIVER(S) NAME(S): ....

ADDRESS: ....

....

PHONE: .... WORK PHONE: ....

MOBILE: .... FAX: ....

EMAIL: ....

PREFERRED CONTACT TIME: ....

PREFERRED MODE OF CONTACT: PHONE / WORK PHONE / FAX / MOBILE

DETAILS OF PARTICIPANT'S AUDIOLOGIST

NAME: ....

COMPANY: ....

ADDRESS: ....

....

PH: .... FAX: ....

CONSENT TO RELEASE OF AUDIOLOGICAL AND OTOLARYNGOLOGY RECORDS

I consent to letting the researchers access my audiological and otolaryngology files for the purposes of this study.

Signed on behalf of:...(full name)

Signed by: ....(full name)

SIGNATURE:.. DATE:..

SPECIAL REQUIREMENTS

I require a sign language interpreter to be present during all appointments ☐ (tick if required)

PLEASE RETURN A COMPLETED CONSENT FORM IN THE PREPAID ENVELOPE TO THE FOLLOWING ADDRESS:

Chris Radford, c/o Department of Communication Disorders,
The University of Canterbury, Private Bag 4800, CHRISTCHURCH 8020

Appendix VII: Group B Information Pack

The information pack for Group B participants included the following:

- A copy of the participant statement of rights (see appendix VI);
- A Group B invitation letter;
- A copy of the information sheet for parents/caregivers of children in Group B;
- A copy of the information sheet for children in Group B and/or a copy of the information sheet for adolescents in Group B, and;
- A New Zealand consent form for participants in Group B

Also included were a pre-paid return envelope and a return slip (illustrated below) for those who preferred not to take part in the study.

I DO NOT WANT MY CHILD TO PARTICIPATE IN THIS STUDY

IF YOU DO NOT WISH FOR YOUR CHILD TO PARTICIPATE IN THIS STUDY PLEASE RETURN THIS SLIP IN THE ATTACHED PRE-PAID ENVELOPE TO THE FOLLOWING ADDRESS BY SUNDAY JULY 13, 2008. PLEASE DO NOT HESITATE TO CONTACT US IF YOU HAVE ANY QUESTIONS REGARDING THE STUDY. THANK YOU FOR YOUR CONSIDERATION.

Chris Radford, c/o Department of Communication Disorders,

Dear parents/caregivers,

We write to you today to inform you about a research study being conducted at the University of Canterbury that may be of interest to you as a parent of a child who uses a cochlear implant (CI).

CIs currently provide a perception of hearing to over four hundred New Zealanders with severe to profound hearing loss. Advances in implant technology mean that CIs are now capable of providing the majority of user's with good open-set speech perception.

Current practice in New Zealand is to implant only one ear. However the brain is designed to work best with input from both ears. A lack of input from both ears results in significant difficulties in the lives of CI users including difficulty locating sounds within their environments, and a relatively poor ability to understand speech in noisy or reverberant environments.

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of CI users who have enough hearing left in that ear. This setup is known as bimodal hearing - the HA provides acoustic stimulation, whereas the CI provides electrical stimulation. The acoustic stimulation provided by the HA may provide the brain with additional information that is not typically conveyed by a CI. This information can potentially improve a CI user's performance in more complex listening tasks, such as perceiving speech in noise and music.

A study investigating the effects of bimodal stimulation on the speech and pitch perception abilities of children with CIs is being conducted as part of a Master's Thesis at the University of Canterbury, in conjunction with the Southern Cochlear Implant Program (SCIP).

Records at the SCIP suggest that your child is a current CI user. We write to you invite your child to participate as a member of GROUP B of our study.

The study would involve two appointments to take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Appointments can be organized outside of school hours, during the weekend and, where appropriate, in the evenings. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch. Where participants reside outside the Canterbury region, a contribution will be made towards travel costs to/from Christchurch. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city.

At the first appointment your child's hearing thresholds will be assessed, in addition to their performance on tests of speech and pitch perception when using their CI. They would then be re-assessed on the same tests of speech and pitch perception at a second appointment twelve to sixteen weeks after the first. This testing is required to account for any learning effects for CI users over the period of the study. While it is not expected that your child will gain any direct benefit from the testing involved in this study, this project has the potential to benefit current and future CI users, their parents and their families, by providing the

SCIP with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

More detail is provided in the attached information sheet, and we would be more than happy to answer any further questions that you may have. Our contact numbers are listed below. If you are able to assist us by allowing your child to participate in this study, we would be most appreciative if you could please complete the attached consent forms, and return them in the pre-paid envelope provided by SUNDAY JULY 13. If you are unable to participate in this study, we would appreciate it if you could return the separate slip and return it to us in the enclosed envelope; this just allows us to keep a track of replies received for this study. Again, please do not hesitate to contact us if you need any more information on this study.

Thank you for your time and consideration.

Sincerely,

Christopher Radford
Masters of Audiology Student
PH: (03) 366 7001 ext: 4816
EMAIL: cjr120@student.canterbury.ac.nz

Valerie Looi
Lecturer in Audiology
(03) 366 7001 ext: 3051
valerie.looi@canterbury.ac.nz

Paul Peryman
Senior Audiologist
(03) 326 6009
pperyman@vanasch.school.nz

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

INFORMATION FOR PARENTS OF PARTICIPANTS IN RESEARCH

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

AIMS OF THE RESEARCH

The main aim of this study is to investigate whether the addition of a hearing aid (HA) can provide children with cochlear implants (CIs) with any additional benefits for perceiving speech and/or pitch. It will also compare whether there are differences between child users of a CI, and child users of HAs in their ability to perceive speech and/or pitch.

It is hoped that the results of this study will help inform clinical practice, and be used to lobby the Government and other funding bodies for increased funding for the cochlear implant program.

PARTICIPATION CRITERIA

Four groups of children will be involved:

GROUP A Children who have used a CI for at least 6 months, have aidable levels of hearing in their non-implanted ear, and are willing to trial a HA in that ear for 3 months;

GROUP B Children who have used a CI-only for 6 months or longer; and

GROUP C Children who have used HA(s)-only for 6 months or longer

GROUP D Children who have used a CI and HA together for 6 months or longer

Your child has been suggested as a potential candidate in the group on the attached invitation letter. Participation in this study in addition to any testing conducted as part of your local Cochlear Implant Program's audiological management, or normal audiological testing for group C. You are free to withdraw your child from this study at any time, without penalty nor affect on their current/future audiological care.

DESCRIPTION OF THE PROCEDURE

GROUP A

Children in group A would be required to attend 4 appointments. The first two appointments are required for the fitting of a HA to your child's non-implanted ear. The initial two appointments will be with your child's local audiologist. If you live in Christchurch you may also choose to have the aid fitted by an audiologist from the University of Canterbury Speech and Hearing Clinic.

The first two sessions should be around 1 hour in duration each. In the first session the audiologist will measure the hearing levels in your child's non-implanted ear, and select the most appropriate HA for your child in consultation with you. An earmould impression will then be taken and sent for earmould

manufacture. A second appointment will be held once the audiologist has received the HA and earmould (approximately 2 -3 weeks later). The HA will then be appropriately fitted to your child. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant) when using their CI. Appropriate counselling regarding the use and management of HAs will be provided at this appointment. Your child will then be required to wear the HA with their CI for approximately 2-3 weeks prior to the third appointment.

The third and fourth appointments will take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city.

The third appointment will be approximately two hours long and be broken into two parts. Your child will first be assessed on tests of speech and pitch perception when listening through their CI only. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes (i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. These tests will take approximately 90 minutes.

After this, your child's HA will be optimised for use with the CI. This involves making adjustments to the HA in order for the loudness levels of both devices to be equated. Your child will need to make comparisons regarding the loudness of different speech materials (sentences) presented using an audiovisual presentation. No changes to the MAP settings on your child's CI will be made and any the details of changes made to the HA will be forwarded to their audiologist. Once optimisation has been completed your child will need to use both the HA in conjunction with the CI for three months.

At the end of this three month period your child would need to attend a final appointment, again held at the University of Canterbury Speech and Hearing Clinic in Christchurch. In this appointment the tests of speech and pitch perception performed in appointment three will be re-administered, however this time your child will be listening using both their CI and the HA. You will be asked to fill in a similar questionnaire as in appointment three, however this one will be to assess your views and experiences in relation to your child's performance when using the CI and HA together.

At the end of the study your child is welcome to keep the HA should you or your child wish, or you can return the HA if you prefer. There will be no charge for the HA.

GROUPS B AND C

Children in groups B and C would be required to attend two appointments, approximately three months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at University of Canterbury Speech and Hearing Clinic and be organised around travel into or around Christchurch wherever possible. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city. The first appointment will last approximately 90 minutes. In the first session your child will be assessed on tests of speech perception and pitch perception, when listening with their CI (Group B) or HAs (Group C). For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes

(i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant). The second appointment will last approximately 90 minutes. The same speech and pitch tests conducted in the first appointment will be re-administered. This is to check test-retest consistency in the results and to account for any improvements in performance for group A over the duration of the study.

GROUP D

Your child would be required to attend 2 appointments, approximately 3 months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at Sydney Cochlear Implant Centre and last approximately 90 minutes. In the sessions your child will be assessed on tests of speech perception and pitch perception, when listening with their CI+HA. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and in the presence of background noise. For the pitch test, they will be required to state whether two notes presented via a loudspeaker go up or down in pitch. In the second appointment these speech and pitch perception tests will be re-administered. This is to check test-retest consistency in the results. You would also be asked to complete a brief parental perspectives questionnaire regarding your child's performance with their CI+HA.

POSSIBLE BENEFIT

Participants in Group A may benefit from improved performance perceiving speech in noise and localising sounds in their environment when listening with both the CI and HA. They will also be able to keep the HA after the study has finished, should they choose to continue using it.

It is not expected that the participants in groups B, C or D will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your local Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

POSSIBLE RISKS

GROUP A

Children in Group A may initially find the sound from the HA unusual, or different, however it is not expected that this would negatively impact on their speech perception ability. However, there is a small risk that some individuals may have greater difficulty hearing with a CI and HA than a CI-only. Parents/ caregivers will be counseled regarding this possibility. Should you find that your child's ability to perceive speech, or their day-to-day functioning is significantly impaired, you are free to discontinue using the HA and/or withdraw from the study at any time, without penalty or impact on your child's audiological care.

Also, your child and/or you may find it more time consuming having to manage 2 devices. Appropriate counseling regarding device usage and maintenance will be provided by your audiologist at the second appointment, and you are welcome to contact the researcher should you have any concerns or questions regarding the fitting of the HA. You will also be able to contact the researcher at any time during the study period (e.g. during the 3 month CI with HA trial), if you have any concerns or questions.

GROUPS B, C AND D

For children in groups B, C, and D the risks associated with the research are not different from those that would be expected in everyday use of the CIs or HAs, or attending a hearing test at an audiology clinic. For all of the testing, the stimuli will be presented at everyday, comfortable levels. Your child will be under the care of a qualified audiologist who will monitor their hearing sensitivity and provide appropriate counseling and support. You will be able to contact the researcher at any time during the study period, if you have any concerns or questions.

COMPLETION OF THE STUDY

It is estimated that this study will be completed by 1st March 2009. Copies of your child's results for this study can be forwarded to your audiologist should you request. It is planned for the research results to be published in appropriate scientific or clinical journals, and the findings may also be presented at international and national conferences or seminars. No information which could lead to your child's identification will be included in any publications or presentations using the data obtained in this study. The Sydney Cochlear Implant Centre, Southern Cochlear Implant Program and Advisors on Deaf Children will be informed of any publications that arise from this study, the details of which can be provided to you if requested.

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

If you have any concerns in regards to any aspect of this research, you are encouraged to contact the principal researcher, Chris Radford.

Should you have any complaints please contact the Department of Communication Disorders, the University of Canterbury, or the supervisors for this project, Valerie Looi or Paul Peryman. f you have any queries or concerns regarding your personal rights, or the rights of your child as a participant in this study feel free to contact an independent Health and Disability Advocate.

CONTACT DETAILS

THE DEPARTMENT OF COMMUNICATION DISORDERS, UNIVERSITY OF CANTERBURY

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Chris Radford, Masters of Audiology Student

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Paul Peryman, Associate Supervisor, Senior Audiologist and Clinical Educator

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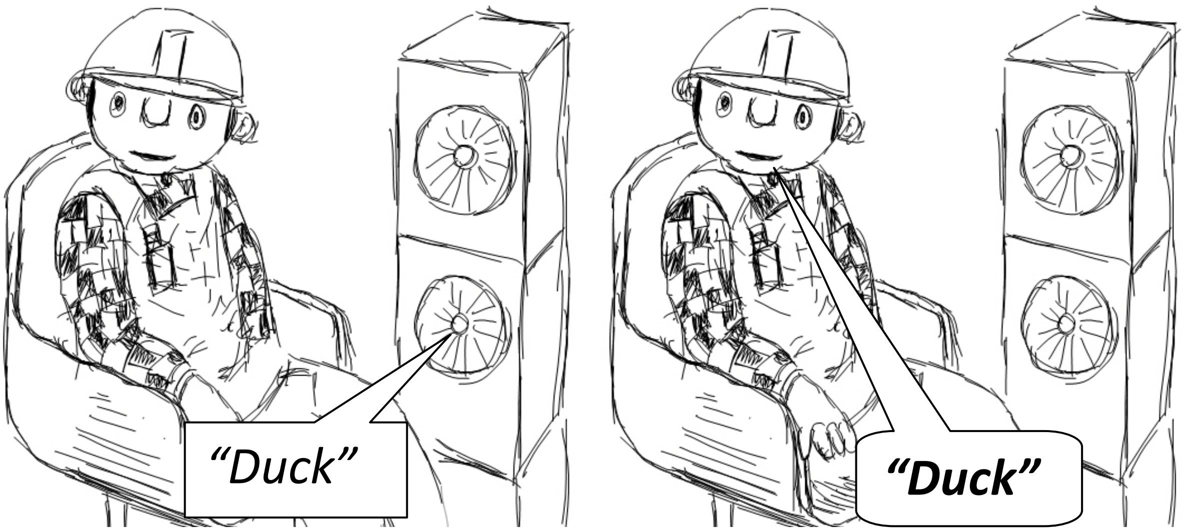
FAX: 0800 2787 7678 (Nationwide) EMAIL: advocacy@hdc.org.nz (Nationwide)

THE UNIVERSITY OF CANTERBURY:
DEPARTMENT OF COMMUNICATION DISORDERS

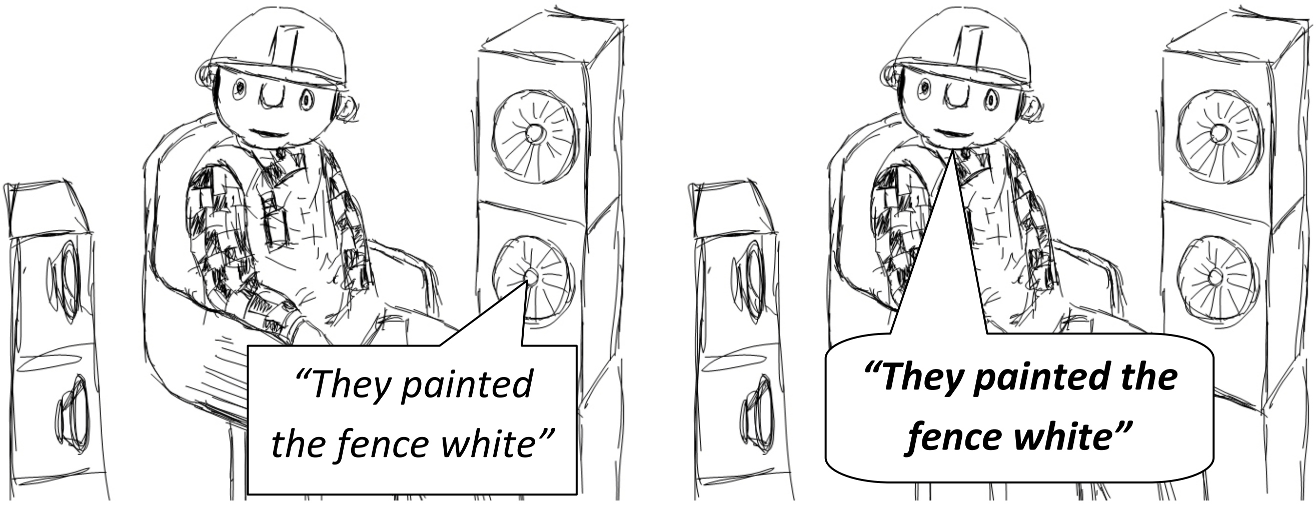
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~5-8

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

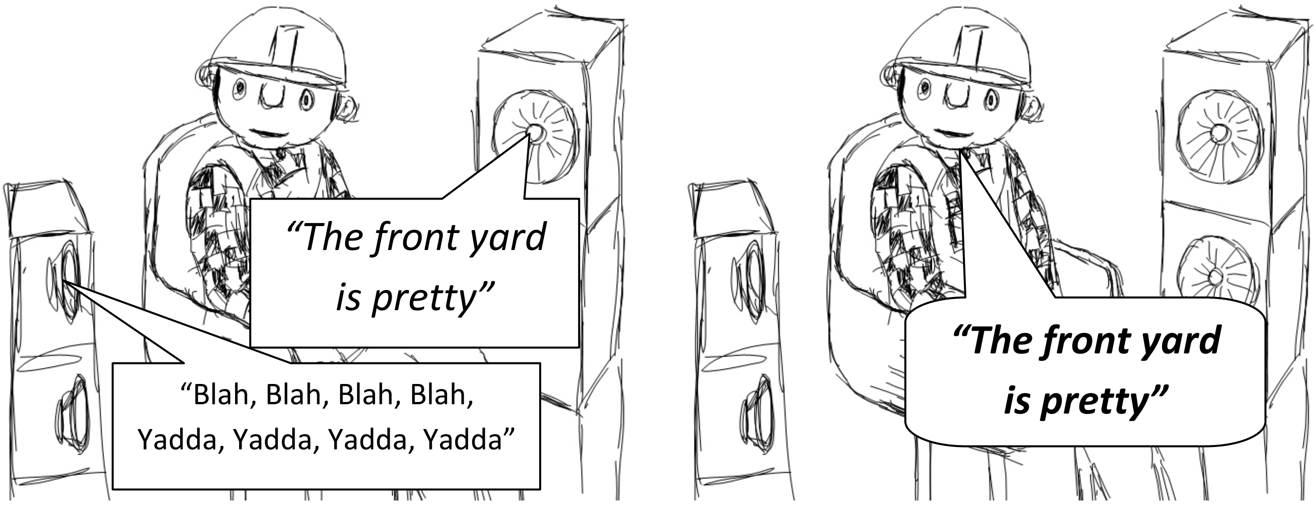
We invite you to take part in a listening game challenge as part of work at the University of Canterbury. Four games will be played, and your aim is to get the high score!



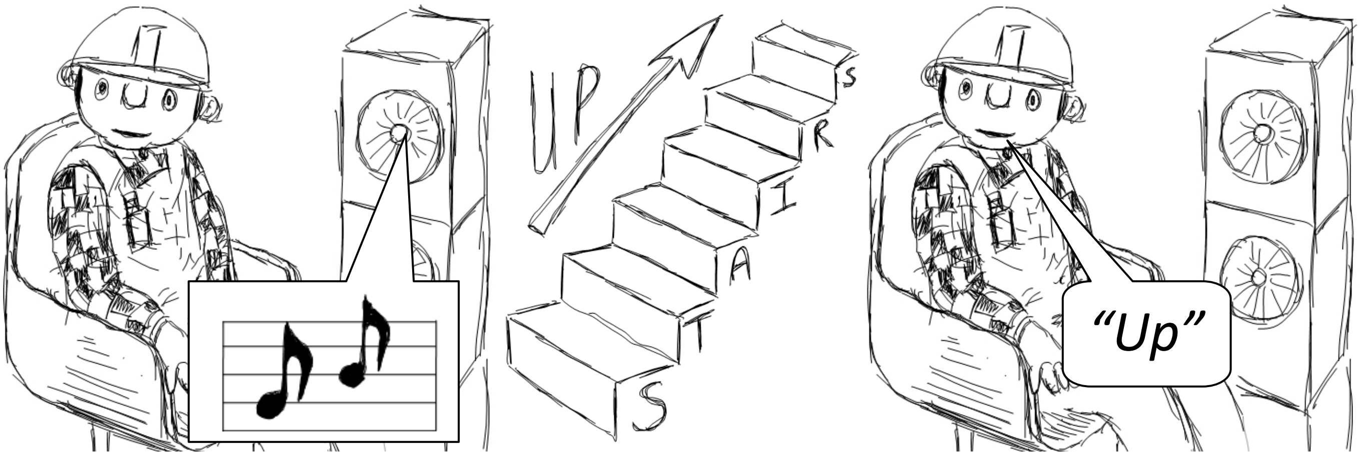
In the first game you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "duck" you say "duck." If you're not sure or don't know what the woman said, have a guess.



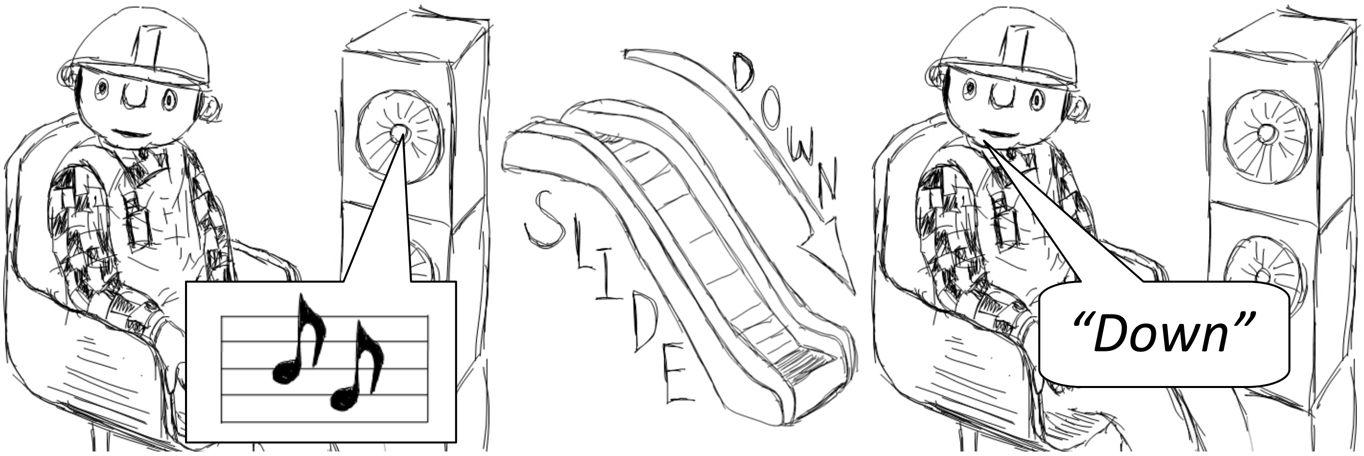
In the second game you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third game you’ll hear a woman say a sentence over a loudspeaker like in the last game. At the same time you’ll also hear a woman ‘babbling’ nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to the sentence the other woman is saying. So if she says “the front yard is pretty” you say “the front yard is pretty.” If you’re not sure or don’t know what the woman said, have a guess.



In the fourth game you’ll hear two notes, played one after another. Your job is to tell us whether they’re going up or down in pitch. If the two notes go up in pitch you say “up”, or point to the picture of the stairs.



If the two notes go down in pitch you say “down”, or point to a picture of a slide. This listening game will be played at three different levels. As you pass each level you’ll be able to score more points.

If you live outside Christchurch you may even make a special trip just to come play these games with us! Good luck, we hope to see you soon!

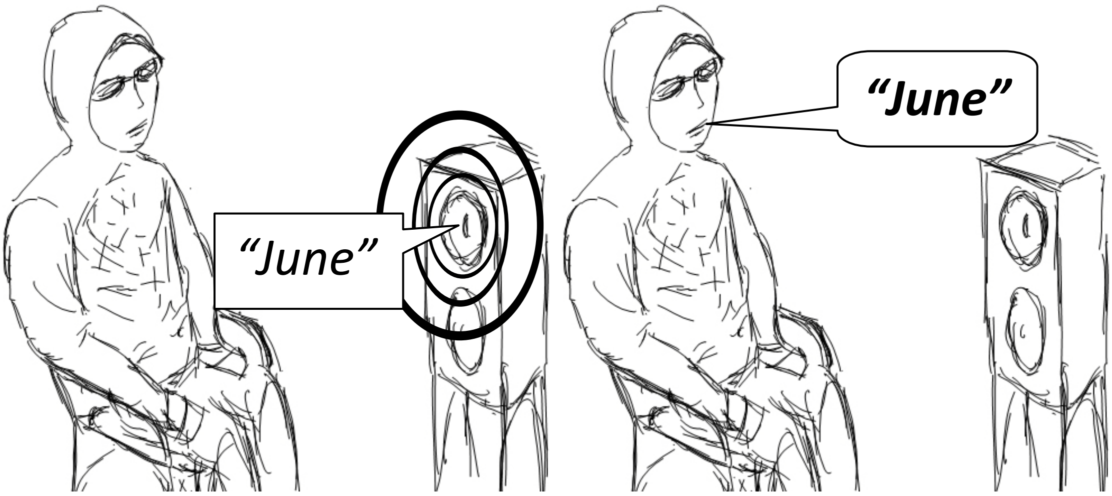
THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~9-16

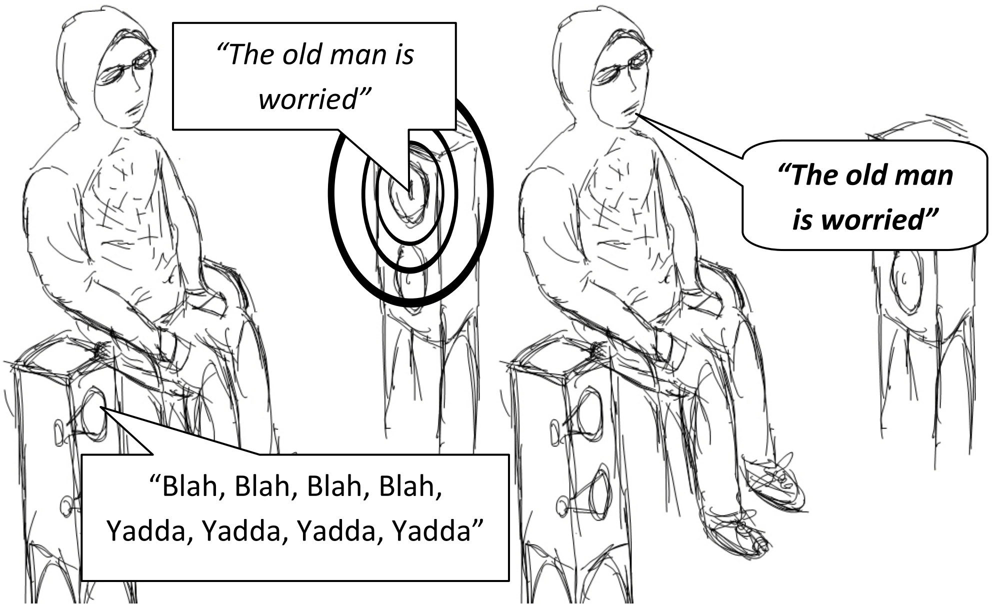
THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

We invite you to take part in a series of listening challenges as part of research at the University of Canterbury. Four challenges are involved, with different levels of difficulty.

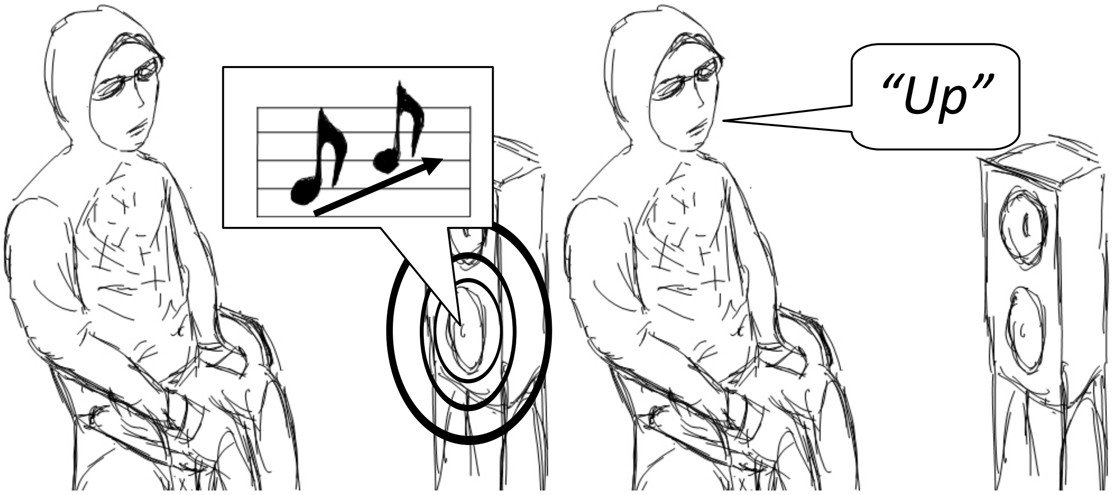


In the first challenge you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the man says "June" you will say "June." If you're not sure or don't know what the woman said, have a guess.

In the second challenge you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you'll say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third challenge you'll hear a woman say a sentence over a loudspeaker as before. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to what the other woman is saying. So if she says "the old man is worried" you say "the old man is worried." If you're not sure or don't know what the woman said, have a guess.



In the fourth challenge you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes rise in pitch you say "up." If the two notes go down in pitch you say "down."

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

Consent Form for Participants in Research

PROJECT TITLE: THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

RESEARCHERS

Christopher Radford	Valerie Looi	Paul Peryman
Masters of Audiology Student	Lecturer in Audiology	Senior Audiologist
PH: (03) 366 7001 ext: 4816	(03) 366 7001 ext: 3051	(03) 326 6009
EMAIL: cjr120@student.canterbury.ac.nz	valerie.looi@canterbury.ac.nz	pperyman@vanasch.school.nz

DECLARATION

I have read and I understand the information sheet for participants taking part in the study designed to investigate the effect of bimodal stimulation on speech and pitch perception in children with cochlear implants dated 13/05/2008. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

I have had the opportunity to use whanau support or a friend to help me ask questions and understand the study.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child from the study at any time and this will in no way affect their future health care, continuing health care, academic progress and/ or employment.

I understand that researchers directly involved in this study may contact my child's audiologist and/or access their audiological files held at their audiology clinic.

I understand that the results of my child's tests are completely confidential, and no material which could identify them will be used in any reports on this study.

I have had the time to consider whether to take part.

I know who to contact if my child has any side effects to any of the procedures, or treatments involved in this study.

I .... (full name) hereby consent for my child

.... (full name) to take part in this study

SIGNATURE .... DATE ....

CONTACT DETAILS OF PARTICIPANT

NAME: .... DATE OF BIRTH: ....

PARENT/CAREGIVER(S) NAME(S): ....

ADDRESS: ....

....

PHONE: .... WORK PHONE: ....

MOBILE: .... FAX: ....

EMAIL: ....

PREFERRED CONTACT TIME: ....

PREFERRED MODE OF CONTACT: PHONE / WORK PHONE / FAX / MOBILE

DETAILS OF PARTICIPANT'S AUDIOLOGIST

NAME: ....

COMPANY: ....

ADDRESS:

....

PH: .... FAX: ....

CONSENT TO RELEASE OF AUDIOLOGICAL AND OTOLARYNGOLOGY RECORDS

I consent to letting the researchers access my audiological and otolaryngology files for the purposes of this study.

Signed on behalf of:.. (full name)

Signed by: .... (full name)

SIGNATURE:.. DATE: ....

SPECIAL REQUIREMENTS

I require a sign language interpreter to be present during all appointments ☐ (tick if required)

PLEASE RETURN A COMPLETED CONSENT FORM IN THE PREPAID ENVELOPE TO THE FOLLOWING ADDRESS:

Chris Radford, c/o Department of Communication Disorders,
The University of Canterbury, Private Bag 4800, CHRISTCHURCH 8020

Appendix VIII: Group C Information Pack

The information pack for Group C participants included the following:

- A copy of the participant statement of rights (see appendix VI);
- A Group C invitation letter;
- A copy of the information sheet for parents/caregivers of children in Group C;
- A copy of the information sheet for children in Group C and/or a copy of the information sheet for adolescents in Group C, and;
- A New Zealand consent form for participants in Group C

Also included were a pre-paid return envelope and a return slip (illustrated below) for those who preferred not to take part in the study.

I DO NOT WANT MY CHILD TO PARTICIPATE IN THIS STUDY

IF YOU DO NOT WISH FOR YOUR CHILD TO PARTICIPATE IN THIS STUDY PLEASE RETURN THIS SLIP IN THE ATTACHED PRE-PAID ENVELOPE TO THE FOLLOWING ADDRESS BY SUNDAY JULY 13, 2008. PLEASE DO NOT HESITATE TO CONTACT US IF YOU HAVE ANY QUESTIONS REGARDING THE STUDY. THANK YOU FOR YOUR CONSIDERATION.

Chris Radford, c/o Department of Communication Disorders,

Dear parents/caregivers,

We write to you today to inform you about a research study being conducted at the University of Canterbury that may be of interest to you as a parent of a child with a significant hearing loss.

Cochlear implants currently provide a perception of hearing to over four hundred New Zealanders with severe to profound hearing loss. Advances in implant technology mean that CIs are now capable of providing the majority of user's with good open-set speech perception.

Current practice in New Zealand is to implant only one ear. However the auditory brain is designed to work best with input from both ears. A lack of input from both ears results in significant difficulties in the lives of CI users including difficulty locating sounds within their environments, and a relatively poor ability to understand speech in noisy or reverberant environments.

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of CI users who have enough hearing left in that ear. This setup is known as bimodal hearing - the HA provides acoustic stimulation, whereas the CI provides electrical stimulation. The acoustic stimulation provided by the HA may provide the brain with additional information that is not typically conveyed by a CI. This information can potentially improve a CI user's performance in more complex listening tasks, such as perceiving speech in noise and listening to music.

A study investigating the effects of bimodal stimulation on the speech and pitch perception abilities of children with CIs is being conducted as part of a Master's Thesis at the University of Canterbury, in conjunction with the Southern Cochlear Implant Program.

Records suggest that your child, is a current HA user. We write to you invite your child to participate as a member of GROUP C of our study.

The study would involve two appointments to take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Appointments can be organized outside of school hours, during the weekend and, where appropriate, in the evenings. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch.

At the first appointment your child's hearing thresholds will be assessed, in addition to their performance on tests of speech and pitch perception when using their HA(s). They would then be re-assessed on the same tests of speech and pitch perception at a second appointment twelve to sixteen weeks after the first. This testing is required to account for any learning effects for HA users over the period of the study. While it is not expected that your child will gain any direct benefit from the testing involved in this study, this project has the potential to benefit current and future CI users, their parents and their families, by providing the Southern Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding. Our study also has the potential to benefit children who use HA(s), by being the first study to report measures of pitch perception for this group.

More detail is provided in the attached information sheet, and we would be more than happy to answer any further questions that you may have. Our contact numbers are listed below. If you are able to assist us by allowing your child to participate in this study, we would be most appreciative if you could please complete the attached consent forms, and return them in the pre-paid envelope provided by SUNDAY JULY 13. If you are unable to participate in this study, we would appreciate it if you could return the separate slip and return it to us in the enclosed envelope; this just allows us to keep a track of replies received for this study. Again, please do not hesitate to contact us if you need any more information on this study.

Thank you for your time and consideration.

Sincerely,

Christopher Radford
Masters of Audiology Student
PH: (03) 366 7001 ext: 4816
EMAIL: cjr120@student.canterbury.ac.nz

Valerie Looi
Lecturer in Audiology
(03) 366 7001 ext: 3051
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Senior Audiologist
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INFORMATION FOR PARENTS OF PARTICIPANTS IN RESEARCH

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

AIMS OF THE RESEARCH

The main aim of this study is to investigate whether the addition of a hearing aid (HA) can provide children with cochlear implants (CIs) with any additional benefits for perceiving speech and/or pitch. It will also compare whether there are differences between child users of a CI, and child users of HAs in their ability to perceive speech and/or pitch.

It is hoped that the results of this study will help inform clinical practice, and be used to lobby the Government and other funding bodies for increased funding for the cochlear implant program.

PARTICIPATION CRITERIA

Four groups of children will be involved:

GROUP A Children who have used a CI for at least 6 months, have aidable levels of hearing in their non-implanted ear, and are willing to trial a HA in that ear for 3 months;

GROUP B Children who have used a CI-only for 6 months or longer; and

GROUP C Children who have used HA(s)-only for 6 months or longer

GROUP D Children who have used a CI and HA together for 6 months or longer

Your child has been suggested as a potential candidate in the group on the attached invitation letter. Participation in this study in addition to any testing conducted as part of your local Cochlear Implant Program's audiological management, or normal audiological testing for group C. You are free to withdraw your child from this study at any time, without penalty nor affect on their current/future audiological care.

DESCRIPTION OF THE PROCEDURE

GROUP A

Children in group A would be required to attend 4 appointments. The first two appointments are required for the fitting of a HA to your child's non-implanted ear. The initial two appointments will be with your child's local audiologist. If you live in Christchurch you may also choose to have the aid fitted by an audiologist from the University of Canterbury Speech and Hearing Clinic.

The first two sessions should be around 1 hour's duration each. In the first session the audiologist will measure the hearing levels in your child's non-implanted ear, and select the most appropriate HA for your child in consultation with you. An earmould impression will then be taken and sent for earmould

manufacture. A second appointment will be held once the audiologist has received the HA and earmould (approximately 2 -3 weeks later). The HA will then be appropriately fitted to your child. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant) when using their CI. Appropriate counselling regarding the use and management of HAs will be provided at this appointment. Your child will then be required to wear the HA with their CI for approximately 2-3 weeks prior to the third appointment.

The third and fourth appointments will take place at the University of Canterbury Speech and Hearing Clinic in Christchurch. Where feasible, for subjects from out of Christchurch, testing will be arranged to co-ordinate with trips made into Christchurch. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city.

The third appointment will be approximately two hours long and be broken into two parts. Your child will first be assessed on tests of speech and pitch perception when listening through their CI only. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes (i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. These tests will take approximately 90 minutes.

After this, your child's HA will be optimised for use with the CI. This involves making adjustments to the HA in order for the loudness levels of both devices to be equated. Your child will need to make comparisons regarding the loudness of different speech materials (sentences) presented using an audiovisual presentation. No changes to the MAP settings on your child's CI will be made and any the details of changes made to the HA will be forwarded to their audiologist. Once optimisation has been completed your child will need to use both the HA in conjunction with the CI for three months.

At the end of this three month period your child would need to attend a final appointment, again held at the University of Canterbury Speech and Hearing Clinic in Christchurch. In this appointment the tests of speech and pitch perception performed in appointment three will be re-administered, however this time your child will be listening using both their CI and the HA. You will be asked to fill in a similar questionnaire as in appointment three, however this one will be to assess your views and experiences in relation to your child's performance when using the CI and HA together.

At the end of the study your child is welcome to keep the HA should you or your child wish, or you can return the HA if you prefer. There will be no charge for the HA.

GROUPS B AND C

Children in groups B and C would be required to attend two appointments, approximately three months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at University of Canterbury Speech and Hearing Clinic and be organised around travel into or around Christchurch wherever possible. A contribution towards the cost of travel is available for those residing outside the Canterbury region. Participants will be reimbursed for the cost of travel to and from appointments within Christchurch city. The first appointment will last approximately 90 minutes. In the first session your child will be assessed on tests of speech perception and pitch perception, when listening with their CI (Group B) or HAs (Group C). For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background noise. For the pitch test, they will be required to state which of two notes

(i.e. 1st or 2nd) also presented via a loudspeaker, is higher in pitch. At the same time we will ask you to respond to a questionnaire which asks your opinion on your child's listening abilities in a range of different listening situations (e.g. a quiet room, or a restaurant). The second appointment will last approximately 90 minutes. The same speech and pitch tests conducted in the first appointment will be re-administered. This is to check test-retest consistency in the results and to account for any improvements in performance for group A over the duration of the study.

GROUP D

Your child would be required to attend 2 appointments, approximately 3 months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at Sydney Cochlear Implant Centre and last approximately 90 minutes. In the sessions your child will be assessed on tests of speech perception and pitch perception, when listening with their CI+HA. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and in the presence of background noise. For the pitch test, they will be required to state whether two notes presented via a loudspeaker go up or down in pitch. In the second appointment these speech and pitch perception tests will be re-administered. This is to check test-retest consistency in the results. You would also be asked to complete a brief parental perspectives questionnaire regarding your child's performance with their CI+HA.

POSSIBLE BENEFIT

Participants in Group A may benefit from improved performance perceiving speech in noise and localising sounds in their environment when listening with both the CI and HA. They will also be able to keep the HA after the study has finished, should they choose to continue using it.

It is not expected that the participants in groups B, C or D will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your local Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

POSSIBLE RISKS

GROUP A

Children in Group A may initially find the sound from the HA unusual, or different, however it is not expected that this would negatively impact on their speech perception ability. However, there is a small risk that some individuals may have greater difficulty hearing with a CI and HA than a CI-only. Parents/ caregivers will be counseled regarding this possibility. Should you find that your child's ability to perceive speech, or their day-to-day functioning is significantly impaired, you are free to discontinue using the HA and/or withdraw from the study at any time, without penalty or impact on your child's audiological care.

Also, your child and/or you may find it more time consuming having to manage 2 devices. Appropriate counseling regarding device usage and maintenance will be provided by your audiologist at the second appointment, and you are welcome to contact the researcher should you have any concerns or questions regarding the fitting of the HA. You will also be able to contact the researcher at any time during the study period (e.g. during the 3 month CI with HA trial), if you have any concerns or questions.

GROUPS B, C AND D

For children in groups B, C, and D the risks associated with the research are not different from those that would be expected in everyday use of the CIs or HAs, or attending a hearing test at an audiology clinic. For all of the testing, the stimuli will be presented at everyday, comfortable levels. Your child will be under the care of a qualified audiologist who will monitor their hearing sensitivity and provide appropriate counseling and support. You will be able to contact the researcher at any time during the study period, if you have any concerns or questions.

COMPLETION OF THE STUDY

It is estimated that this study will be completed by 1st March 2009. Copies of your child's results for this study can be forwarded to your audiologist should you request. It is planned for the research results to be published in appropriate scientific or clinical journals, and the findings may also be presented at international and national conferences or seminars. No information which could lead to your child's identification will be included in any publications or presentations using the data obtained in this study. The Sydney Cochlear Implant Centre, Southern Cochlear Implant Program and Advisors on Deaf Children will be informed of any publications that arise from this study, the details of which can be provided to you if requested.

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

If you have any concerns in regards to any aspect of this research, you are encouraged to contact the principal researcher, Chris Radford.

Should you have any complaints please contact the Department of Communication Disorders, the University of Canterbury, or the supervisors for this project, Valerie Looi or Paul Peryman. f you have any queries or concerns regarding your personal rights, or the rights of your child as a participant in this study feel free to contact an independent Health and Disability Advocate.

CONTACT DETAILS: MAIN CONTACT PH: **+64 (3) 366 7001 EXT: 4295**

THE DEPARTMENT OF COMMUNICATION DISORDERS, UNIVERSITY OF CANTERBURY

PH: +64 (3) 364 2431 (General) FAX: +64 (3) 364 2760 CLINIC PH: +64 (3) 364 2408

CHRIS RADFORD, Masters of Audiology Student

PH: +64 (3) 366 7001 ext: 4295 EMAIL: cjr120@student.canterbury.ac.nz MOB: +64 21 034 0744

VALERIE LOOI, Primary Supervisor, Lecturer in Audiology

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PAUL PERYMAN, Associate Supervisor, Senior Audiologist and Clinical Educator

PH: +64 (3) 326 6009 EMAIL: pperyman@vanasch.school.nz

HEALTH AND DISABILITY ADVOCATE SERVICES

PH: 0800 423 638 (Lower North Island) PH: 0800 377 766 (South Island)

FAX: 0800 2787 7678 (Nationwide) EMAIL: advocacy@hdc.org.nz (Nationwide)

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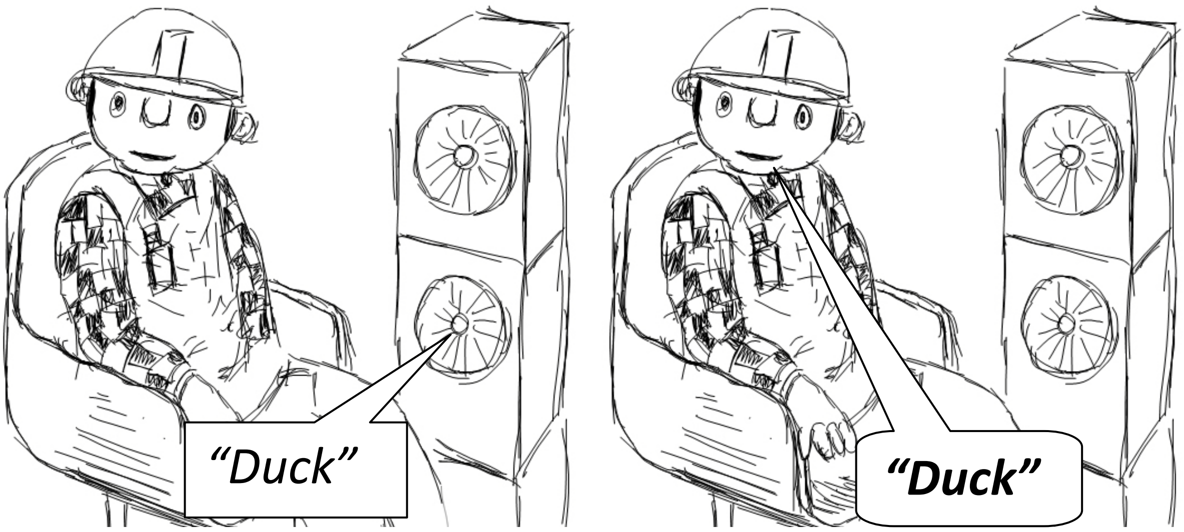
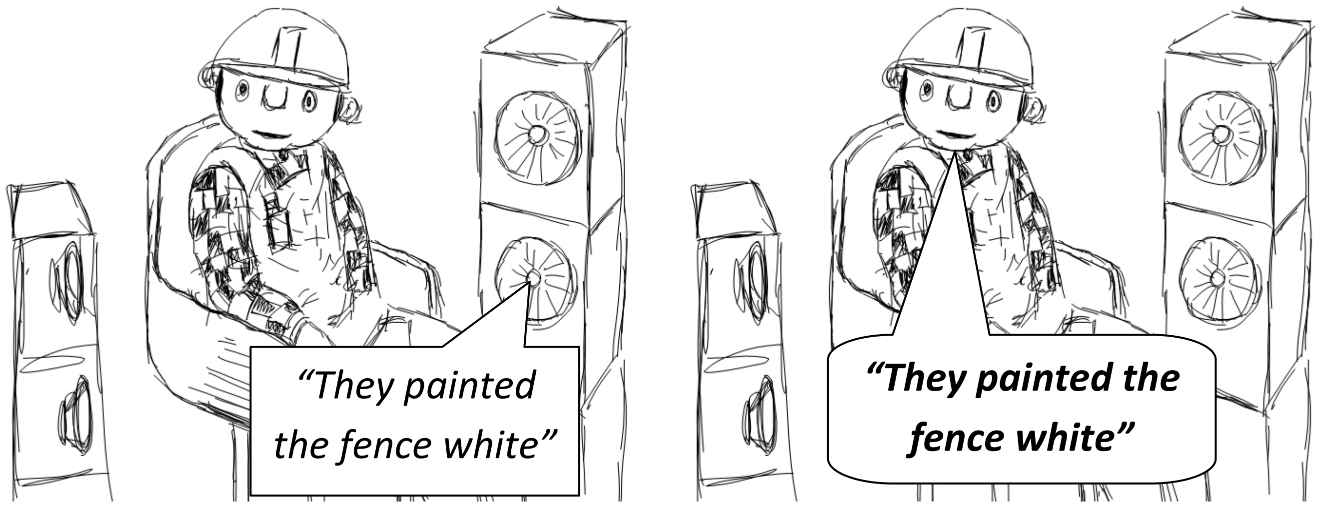
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~5-8

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

We invite you to take part in a listening game challenge as part of work at the University of Canterbury. Four games will be played, and your aim is to get the high score!

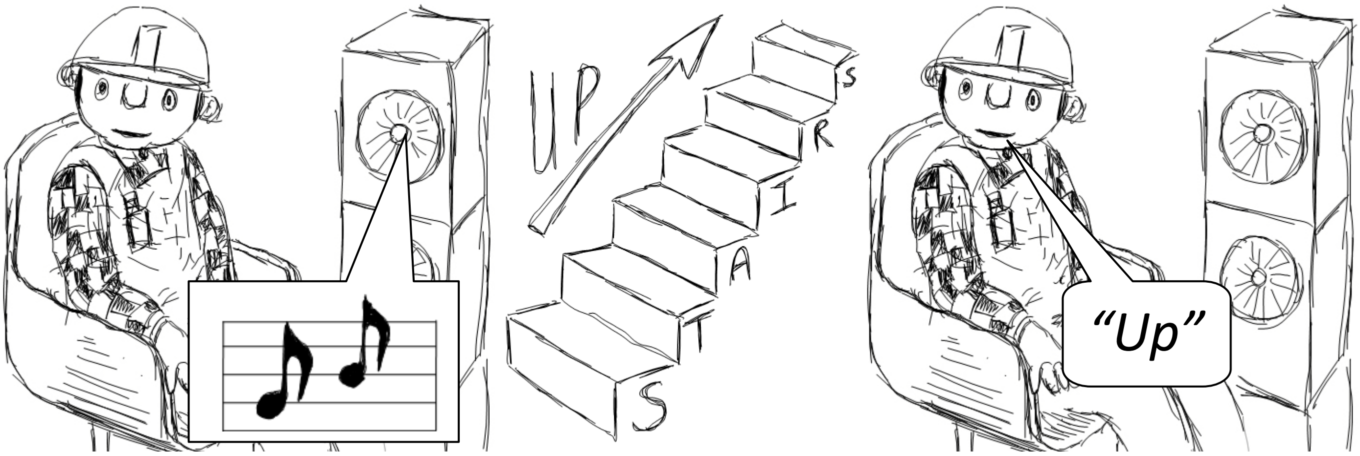


In the first game you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "duck" you say "duck." If you're not sure or don't know what the woman said, have a guess.

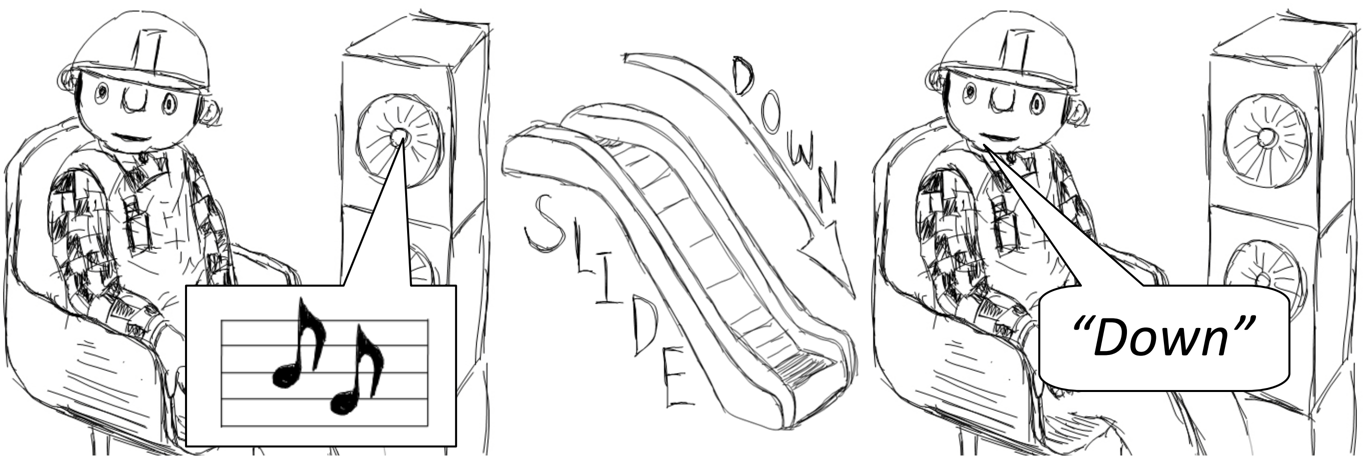


In the second game you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.

In the third game you’ll hear a woman say a sentence over a loudspeaker like in the last game. At the same time you’ll also hear a woman ‘babbling’ nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to the sentence the other woman is saying. So if she says “the front yard is pretty” you say “the front yard is pretty.” If you’re not sure or don’t know what the woman said, have a guess.



In the fourth game you’ll hear two notes, played one after another. Your job is to tell us whether they’re going up or down in pitch. If the two notes go up in pitch you say “up”, or point to the picture of the stairs.



If the two notes go down in pitch you say “down”, or point to a picture of a slide. This listening game will be played at three different levels. As you pass each level you’ll be able to score more points.

If you live outside Christchurch you may even make a special trip just to come play these games with us! Good luck, we hope to see you soon!

THE UNIVERSITY OF CANTERBURY:

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INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~9-16

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

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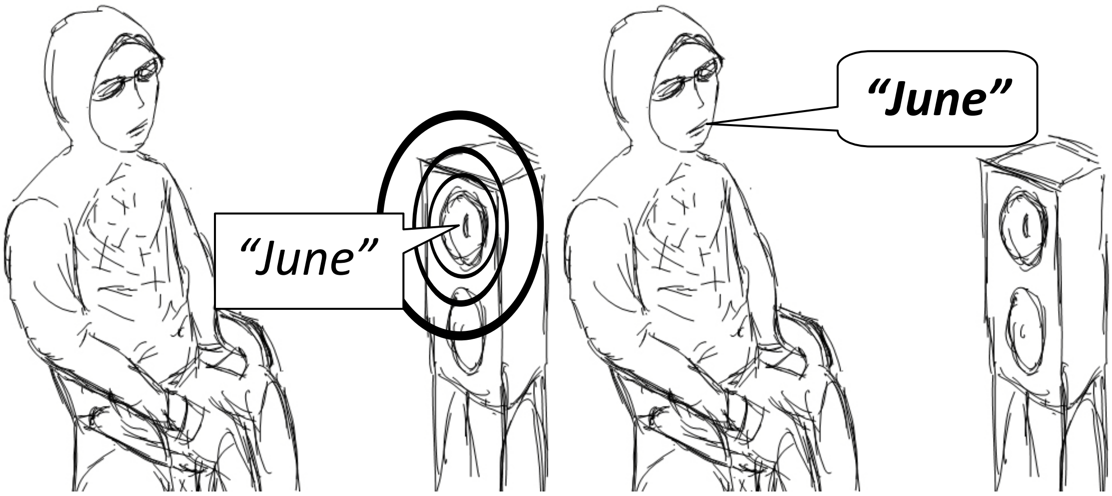
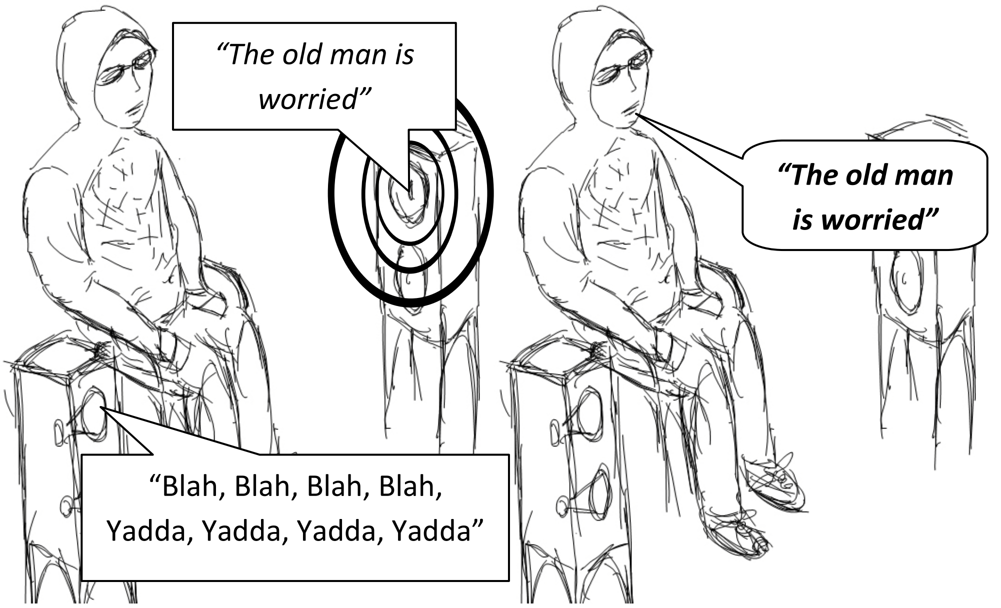
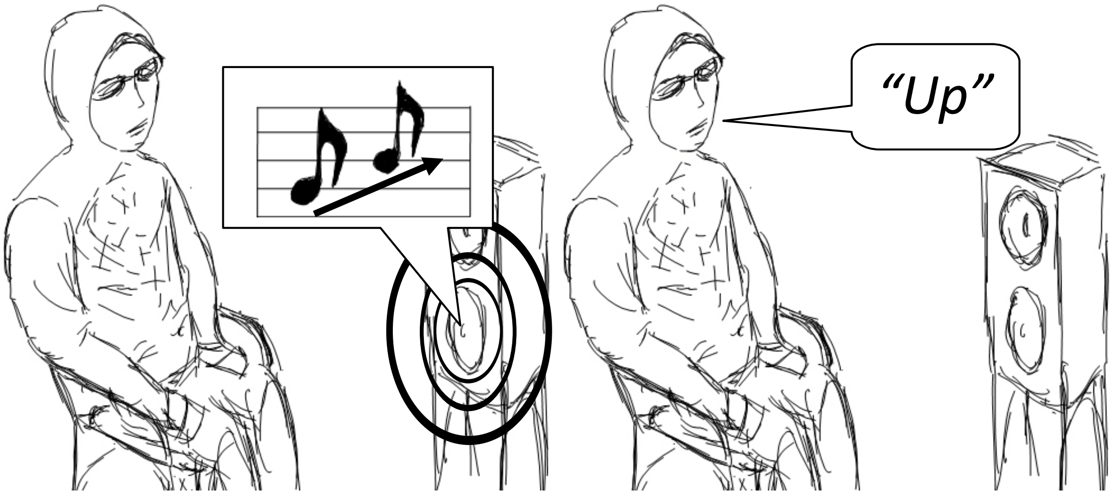


In the first challenge you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "June" you will say "June." If you're not sure or don't know what the woman said, have a guess.

In the second challenge you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you'll say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third challenge you'll hear a woman say a sentence over a loudspeaker as before. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to what the other woman is saying. So if she says "the old man is worried" you say "the old man is worried." If you're not sure or don't know what the woman said, have a guess.



In the fourth challenge you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes rise in pitch you say "up." If the two notes go down in pitch you say "down."

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UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Consent Form for Participants in Research

PROJECT TITLE: THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

RESEARCHERS

Christopher Radford	Valerie Looi	Paul Peryman
Masters of Audiology Student	Lecturer in Audiology	Senior Audiologist
PH: (03) 366 7001 ext: 4816	(03) 366 7001 ext: 3051	(03) 326 6009
EMAIL: cjr120@student.canterbury.ac.nz	valerie.looi@canterbury.ac.nz	pperyman@vanasch.school.nz

DECLARATION

I have read and I understand the information sheet for participants taking part in the study designed to investigate the effect of bimodal stimulation on speech and pitch perception in children with cochlear implants dated 13/05/2008. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

I have had the opportunity to use whanau support or a friend to help me ask questions and understand the study.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child from the study at any time and this will in no way affect their future health care, continuing health care, academic progress and/ or employment.

I understand that researchers directly involved in this study may contact my child's audiologist and/or access their audiological files held at their audiology clinic.

I understand that the results of my child's tests are completely confidential, and no material which could identify them will be used in any reports on this study.

I have had the time to consider whether to take part.

I know who to contact if my child has any side effects to any of the procedures, or treatments involved in this study.

I .... (full name) hereby consent for my child

.... (full name) to take part in this study

SIGNATURE .... DATE..

CONTACT DETAILS OF PARTICIPANT

NAME: .... DATE OF BIRTH: ....

ADDRESS: ....

....

PHONE: .... WORK PHONE: ....

MOBILE: .... FAX: ....

EMAIL: ....

PREFERRED CONTACT TIME: ....

PREFERRED MODE OF CONTACT: PHONE / WORK PHONE / FAX / MOBILE

DETAILS OF PARTICIPANT'S AUDIOLOGIST

NAME: ....

COMPANY: ....

ADDRESS: ....

....

PH: .... FAX: ....

CONSENT TO RELEASE OF AUDIOLOGICAL AND OTOLARYNGOLOGY RECORDS

I consent to letting the researchers access my audiological and otolaryngology files for the purposes of this study.

Signed on behalf of: .... (full name)

Signed by: .... (full name)

SIGNATURE: .... DATE: ....

SPECIAL REQUIREMENTS

I require a sign language interpreter to be present during all appointments ☐ (tick if required)

PLEASE RETURN A COMPLETED CONSENT FORM IN THE PREPAID ENVELOPE TO THE FOLLOWING ADDRESS:

Chris Radford, c/o Department of Communication Disorders,
The University of Canterbury, Private Bag 4800, CHRISTCHURCH 8020

Appendix IX: Group D Information Pack

The information pack for Group D participants included the following:

- A copy of the participant statement of rights (see appendix VI);
- A Group D invitation letter;
- A copy of the information sheet for parents/caregivers of children in Group D;
- A copy of the information sheet for children in Group D and/or a copy of the information sheet for adolescents in Group D, and;
- An Australian consent form for participants in Group D

Also included were a pre-paid return envelope and a return slip (illustrated below) for those who preferred not to take part in the study.

I DO NOT WANT MY CHILD TO PARTICIPATE IN THIS STUDY

IF YOU DO NOT WISH FOR YOUR CHILD TO PARTICIPATE IN THIS STUDY PLEASE RETURN THIS SLIP IN THE ATTACHED PRE-PAID ENVELOPE TO THE FOLLOWING ADDRESS BY SUNDAY JULY 13, 2008. PLEASE DO NOT HESITATE TO CONTACT US IF YOU HAVE ANY QUESTIONS REGARDING THE STUDY. THANK YOU FOR YOUR CONSIDERATION.

Coleen Psarros, c/o Sydney Cochlear Implant Centre,
PO Box 188 Gladesville NSW 1675

Dear parents/caregivers,

We are writing to ask if you child would be able to participate in a research study being conducted as part of a Masters' of Audiology thesis at the University of Canterbury, in conjunction with the Sydney Cochlear Implant Centre (SCIC). The study investigates the effects of bimodal stimulation on the speech and pitch perception abilities of children with cochlear implants (CIs).

A growing body of evidence supports the use of a hearing aid (HA) in the non-implanted ear of CI users who have enough hearing left in that ear (i.e. bimodal hearing). The acoustic stimulation provided by the HA may provide the brain with additional information that is not typically conveyed by a CI. This information can potentially improve a CI user's performance in more complex listening tasks, such as perceiving speech in noise and music.

Records at the SCIC suggest that your child is a current user of bimodal hearing. We write to you invite your child to participate as a member of GROUP D of our study.

The study would involve two appointments to take place at the SCIC. The two appointments would be around 90 minutes each, spaced approximately 3 months apart. At both appointments your child will undertake tests of speech and pitch perception whilst wearing both their CI and HA together. No adjustment to your child's CI or HA will be made as part of this study, nor will there be any 'take home' component. While it is not expected that your child will gain any direct benefit from the testing involved in this study, this project has the potential to benefit current and future CI users, their parents, and their families. It may provide information that could assist in future clinical decision making, and to help lobby Governments for increased funding.

More detail is provided in the attached information sheet, and we would be more than happy to answer any further questions that you may have. Our contact numbers are listed below and on the attached information sheet. Alternatively, you could also contact Coleen Psarros at the SCIC (PH: +61 2 9844 6813; FAX: +61 2 9844 6811). If you are able to assist us by allowing your child to participate in this study, we would be most appreciative if you could please complete the attached consent forms, and return them to the SCIC as soon as possible. Again, please do not hesitate to contact us if you need any more information on this study.

Thank you for your time and consideration.

Sincerely,

Christopher Radford
Masters of Audiology Student
PH: +64 (3) 366 7001 ext: 4816
EMAIL: cjr120@student.canterbury.ac.nz

Valerie Looi
Lecturer in Audiology
+64 (3) 366 7001 ext: 3051
valerie.looi@canterbury.ac.nz

Paul Peryman
Senior Audiologist
+64 (3) 326 6009
pperyman@vanasch.school.nz

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CHRISTCHURCH NEW ZEALAND

INFORMATION FOR PARTICIPANTS IN RESEARCH

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

AIMS OF THE RESEARCH

The main aim of this study is to investigate whether the addition of a hearing aid (HA) can provide children with cochlear implants (CIs) with any additional benefits for perceiving speech and/or pitch. It will also compare whether there are differences between children using CIs to those using HAs and those using both a CI with a HA, in their ability to perceive speech and/or pitch.

It is hoped that the results of this study will help inform clinical practice, and be used to lobby the Government and other funding bodies for increased funding for the cochlear implant program.

PARTICIPATION CRITERIA

Four groups of children will be involved:

GROUP A Children who have used a CI for at least 6 months, have aidable levels of hearing in their non-implanted ear, and are willing to trial a HA in that ear for 3 months;

GROUP B Children who have used a CI-only for 6 months or longer; and

GROUP C Children who have used HA(s)-only for 6 months or longer

GROUP D Children who have used a CI and HA together for 6 months or longer

Your child has been suggested as a potential candidate for Group D. Participation in this study in addition to any testing conducted as part of the Sydney Cochlear Implant Centre's (SCIC) audiological management. You are free to withdraw your child from this study at any time, without penalty nor affect on their current/future audiological care.

DESCRIPTION OF THE PROCEDURE

GROUP D

Your child would be required to attend 2 appointments, approximately 3 months apart. No adjustments to your child's listening device will be made during either appointment. Both appointments will take place at Sydney Cochlear Implant Centre and last approximately 90 minutes. In the sessions your child will be assessed on tests of speech perception and pitch perception, when listening with their CI+HA. For the speech perception tests, they will be asked to verbally repeat speech stimuli (e.g. words or sentences) presented via a loudspeaker, both in quiet and with the presence of background. For the pitch test, they will be required to state whether two notes presented via a loudspeaker go up or down in pitch. In the second appointment these speech and pitch perception tests will be re-administered. This is to check test-retest consistency in the results. You would also be asked to complete a brief parental perspectives questionnaire regarding your child's performance with their CI+HA.

POSSIBLE BENEFIT

It is not expected that your child will obtain any direct benefit from the testing sessions. However the project has the potential to benefit current and future CI users, their parents and their families, by providing your local Cochlear Implant Program with information that could assist in their clinical decision making, and to help lobby the Government for increased funding.

POSSIBLE RISKS

GROUP D

The risks associated with the research are not different from those that would be expected in everyday use of the CIs or HAs, or attending a hearing test at an audiology clinic. For all of the testing, the stimuli will be presented at everyday, comfortable levels. Your child will be under the care of a qualified audiologist who will monitor their hearing sensitivity. You will be able to contact the researcher at any time during the study period, if you have any concerns or questions.

COMPLETION OF THE STUDY

It is estimated that this study will be completed by 1st March 2009. Copies of your child's results for this study can be forwarded to your audiologist should you request. It is planned for the research results to be published in appropriate scientific or clinical journals, and the findings may also be presented at international and national conferences or seminars. No information which could lead to your child's identification will be included in any publications or presentations using the data obtained in this study. The SCIC will be informed of any publications that arise from this study, the details of which can be provided to you if requested.

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee, as well as the New Zealand Health and Disability Multi-Region Ethics Committee.

If you have any concerns in regards to any aspect of this research, you are encouraged to contact the principal researcher, Chris Radford. Should you have any complaints, you are also able to contact either the Department, the Primary Investigator for the research Valerie Looi, or Colleen Psarros at the SCIC. Should you have any complaints feel free to contact, Valerie Looi or Paul Perryman, the supervising investigators for the research or alternatively contact the Department of Communication Disorders and the University of Canterbury.f you have any queries or concerns regarding your personal rights, or the rights of your child as a participant in this study feel free to contact an independent Health and Disability Advocate.

CONTACT DETAILS

THE DEPARTMENT OF COMMUNICATION DISORDERS
UNIVERSITY OF CANTERBURY, NEW ZEALAND

PH: +64 (3) 364 2431 (General) FAX: +64 (3) 364 2760 CLINIC PH: +64 (3) 364 2408

CHRIS RADFORD, MASTERS of AUDIOLOGY STUDENT

PH: 0064 (3) 366 7001 ext: 4816 EMAIL: cjr120@student.canterbury.ac.nz MOB: 0064 21 034 0744

VALERIE LOOI, PRIMARY SUPERVISOR, LECTURER IN AUDIOLOGY

PH: 0064 (3) 366 7001 ext: 3051 EMAIL: valerie.looi@canterbury.ac.nz

PAUL PERYMAN, ASSOCIATE SUPERVISOR, SENIOR AUDIOLOGIST, CLINICAL EDUCATOR

PH: 0064 (3) 326 6009 EMAIL: pperyman@vanasch.school.nz

THE SYDNEY COCHLEAR IMPLANT CENTRE

PH: 0061 (2) 9844 6811 FAX: 0061 (2) 9844 6811

COLLEEN PSARROS, COORDINATOR OF AUDIOLOGICAL RESEARCH AND TRAINING

PH: 0061 (2) 9844 6813 EMAIL: colleen.psarros@scic.nsw.gov.au

DISABILITY ADVOCACY NEW SOUTH WALES

PH: 0061 1300 365 085 EMAIL: da@da.org.au

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DEPARTMENT OF COMMUNICATION DISORDERS

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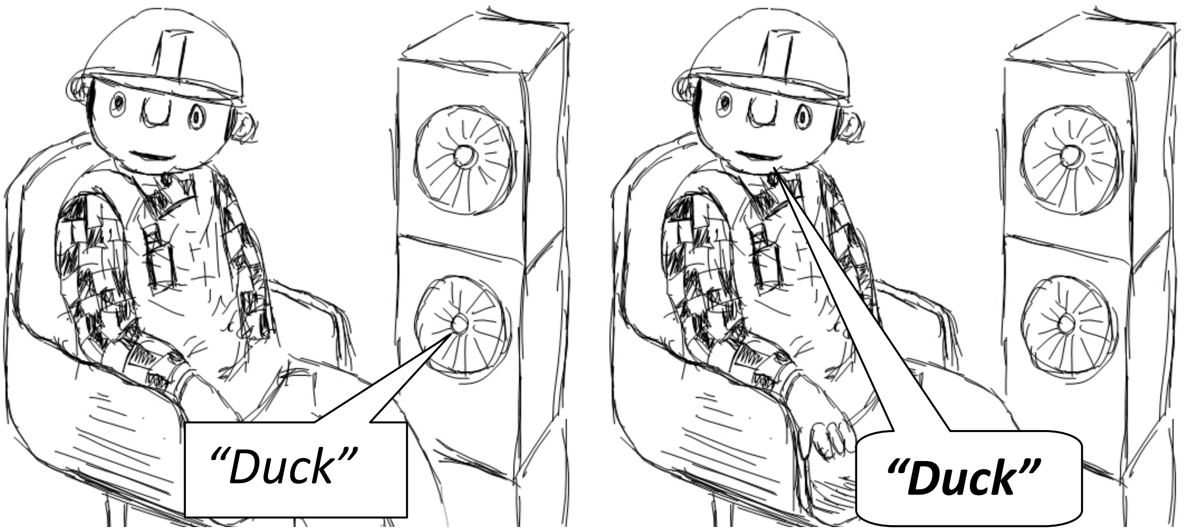
CHRISTCHURCH NEW ZEALAND

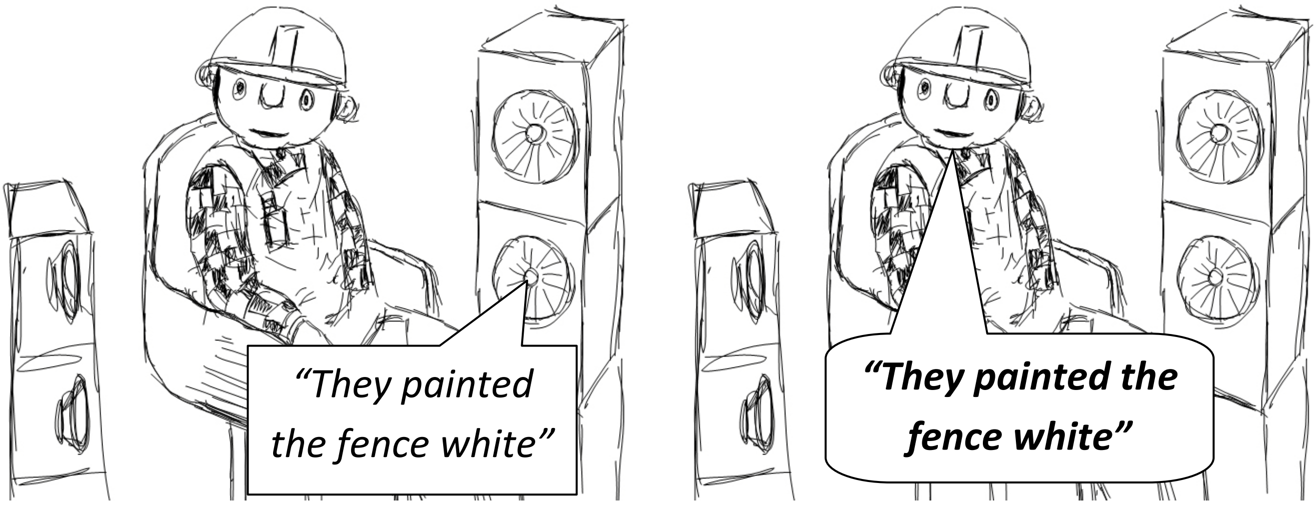
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~5-8

THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

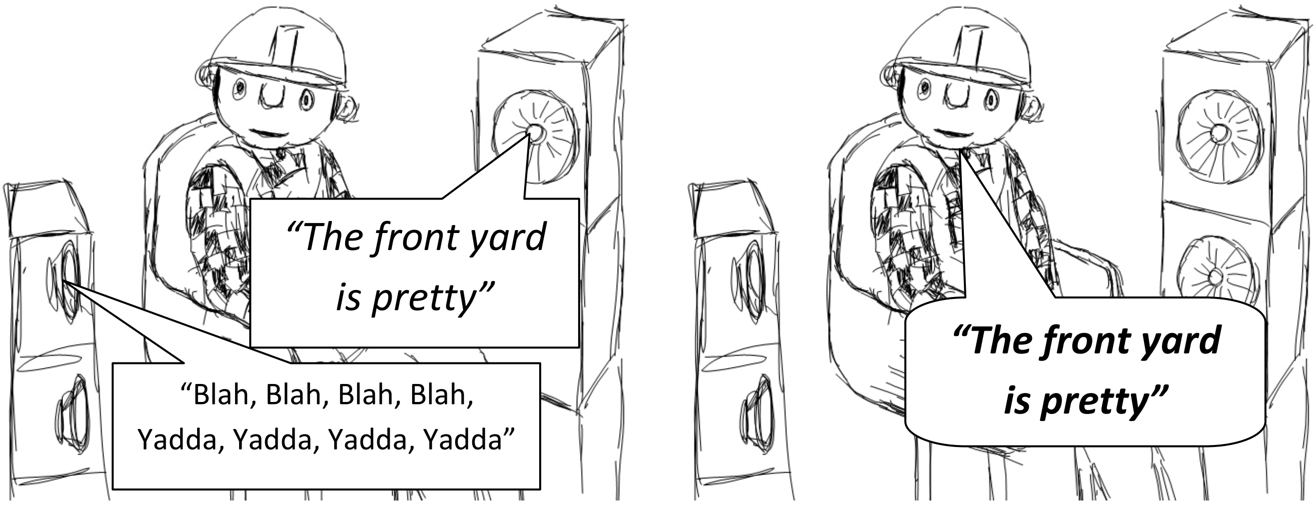
We invite you to take part in a listening game challenge as part of work at the University of Canterbury. Four games will be played, and your aim is to get the high score!



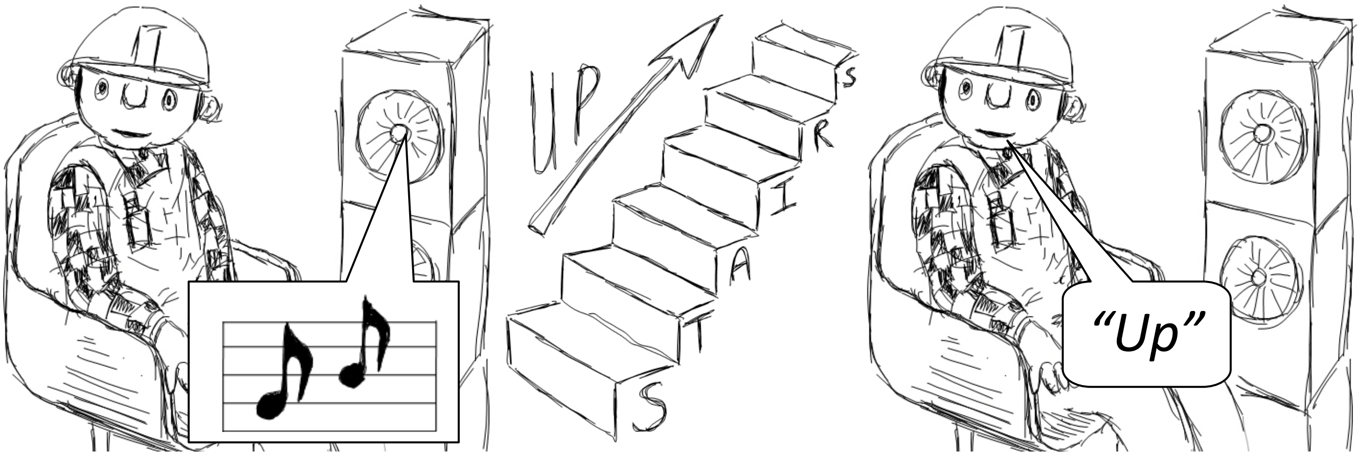
In the first game you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "duck" you say "duck." If you're not sure or don't know what the woman said, have a guess.



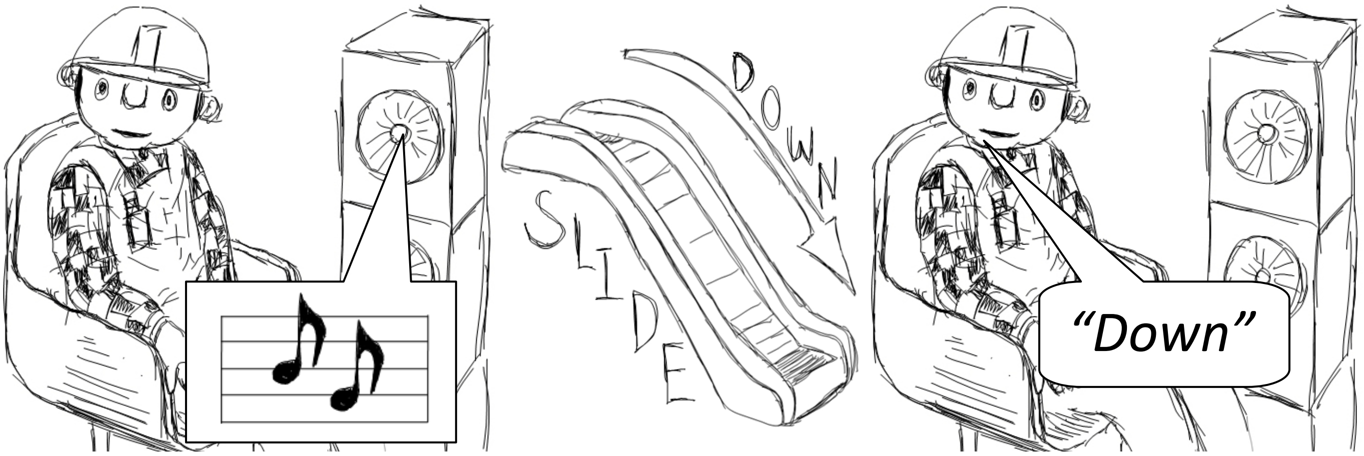
In the second game you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third game you’ll hear a woman say a sentence over a loudspeaker like in the last game. At the same time you’ll also hear a woman ‘babbling’ nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to the sentence the other woman is saying. So if she says “the front yard is pretty” you say “the front yard is pretty.” If you’re not sure or don’t know what the woman said, have a guess.



In the fourth game you’ll hear two notes, played one after another. Your job is to tell us whether they’re going up or down in pitch. If the two notes go up in pitch you say “up”, or point to the picture of the stairs.



If the two notes go down in pitch you say “down”, or point to a picture of a slide. This listening game will be played at three different levels. As you pass each level you’ll be able to score more points.

Good luck, we hope to see you soon!

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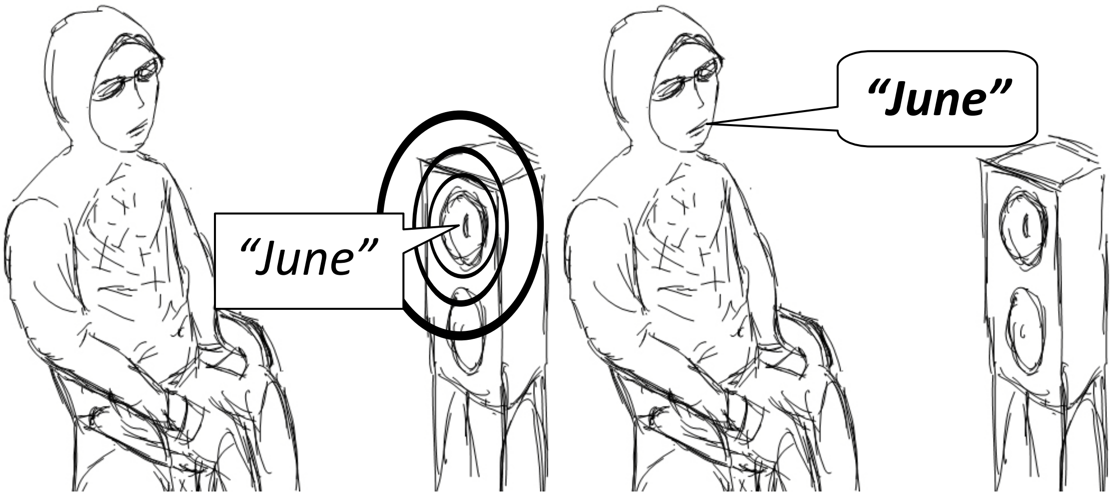
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~9-16

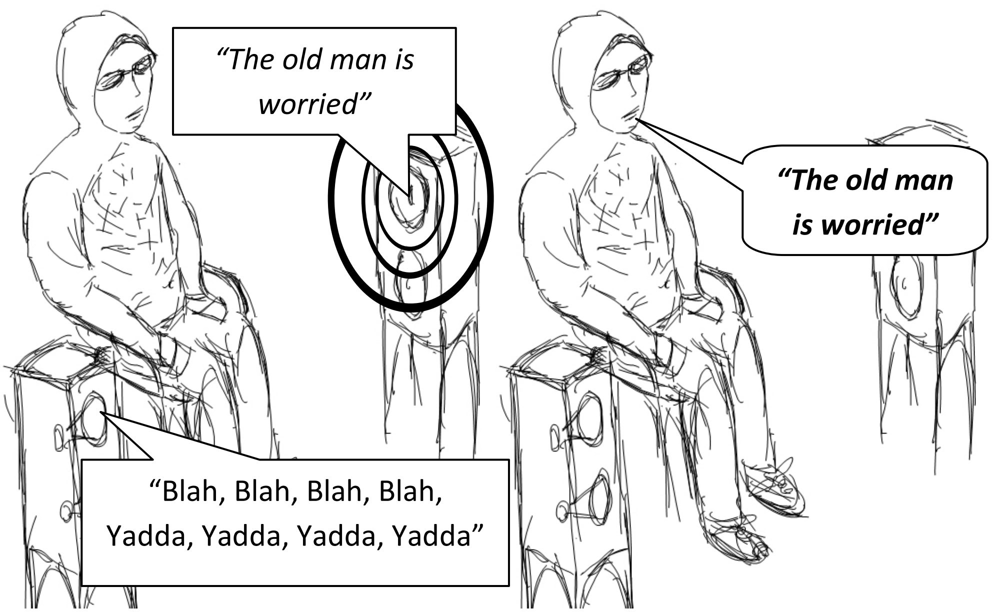
THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

We invite you to take part in a series of listening challenges as part of research at the University of Canterbury. Four challenges are involved, with different levels of difficulty.

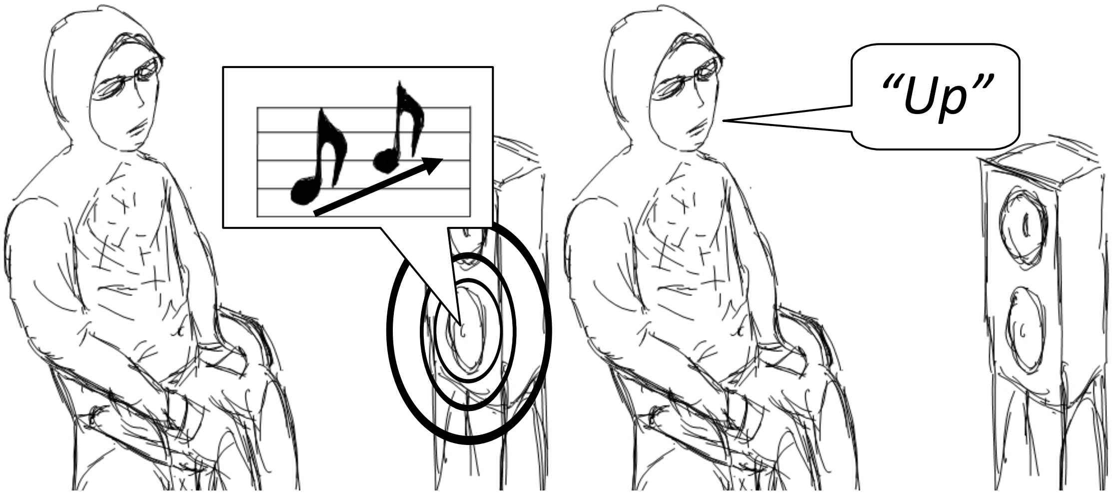


In the first challenge you'll hear a woman talking over a loudspeaker. She will say single words. All you need to do is repeat what the woman says. So if the woman says "June" you will say "June." If you're not sure or don't know what the woman said, have a guess.

In the second challenge you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you'll say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third challenge you'll hear a woman say a sentence over a loudspeaker as before. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to what the other woman is saying. So if she says "the old man is worried" you say "the old man is worried." If you're not sure or don't know what the woman said, have a guess.



In the fourth challenge you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes rise in pitch you say "up." If the two notes go down in pitch you say "down."

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Consent Form for Participants in Research

PROJECT TITLE: THE EFFECT OF BIMODAL STIMULATION ON SPEECH AND PITCH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS

RESEARCHERS

Christopher Radford	Valerie Looi	Paul Peryman
Masters of Audiology Student	Lecturer in Audiology	Senior Audiologist
PH: 0064 (3) 366 7001 ext: 4816	0064 (3) 366 7001 ext: 3051	0064 (3) 326 6009
EMAIL: cjr120@student.canterbury.ac.nz	valerie.looi@canterbury.ac.nz	pperyman@vanasch.school.nz

DECLARATION

I have read and I understand the information sheet for participants taking part in the study designed to investigate the effect of bimodal stimulation on speech and pitch perception in children with cochlear implants. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

I have had the opportunity to use family support or a friend to help me ask questions and understand the study.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child from the study at any time and this will in no way affect their future health care, continuing health care, academic progress and/ or employment.

I understand that researchers directly involved in this study may contact my child's audiologist and/or access their audiological files held at their audiology clinic.

I understand that the results of my child's tests are completely confidential, and no material which could identify them will be used in any reports on this study.

I have had the time to consider whether to take part.

I know who to contact if my child has any side effects to any of the procedures, or treatments involved in this study.

I .... (full name) hereby consent for my child

....(full name) to take part in this study.

SIGNATURE .... DATE...

CONTACT DETAILS OF PARTICIPANT

NAME: .... DATE OF BIRTH: ....

ADDRESS: ....

....

PHONE: .... WORK PHONE: ....

MOBILE: .... FAX: ....

EMAIL: ....

PREFERRED CONTACT TIME: ....

PREFERRED MODE OF CONTACT: PHONE / WORK PHONE / FAX / MOBILE

CONSENT TO RELEASE OF AUDIOLOGICAL AND OTOLARYNGOLOGY RECORDS

I consent to letting the researchers seeing and accessing my audiological and otolaryngology files for the purposes of this study.

Signed on behalf of: .... (full name)

Signed by: .... (full name)

SIGNATURE: .... DATE: ....

SPECIAL REQUIREMENTS

I require a sign language interpreter to be present during all appointments ☐ (tick if required)

PLEASE RETURN A COMPLETED CONSENT FORM IN THE PREPAID ENVELOPE TO THE FOLLOWING ADDRESS:

Colleen Psarros

c/o Sydney Cochlear Implant Centre

PO Box 188

GLADESVILLE

NSW 1675

Appendix X: Group E Information Pack

The information pack for Group E participants included the following:

- A copy of the participant statement of rights (see appendix VI);
- A Group E invitation letter;
- A copy of the information sheet for parents/caregivers of children in Group E;
- A copy of the information sheet for children in Group E and/or a copy of the information sheet for adolescents in Group E, and;
- An Australian consent form for participants in Group E

Advertisement – Version 1.0 12/06/2008

TONE DEAF?

TRAINED MUSICIAN?

KARAOKE ST★R!

We're looking for participants for a study investigating the performance of children on tasks of speech recognition in noise and pitch perception.

Participants should:

- ★ be between 5 and 15 years of age
- ★ have no language-related learning disabilities
- ★ have normal hearing
- ★ be native English speakers

Participation would involve attending a one hour testing session. All testing will take place at the Department of Communication Disorders, University of Canterbury.

The speech perception task involves listening to and repeating short sentences in quiet, and in the presence of four-talker babble noise. The pitch perception task involves listening to a pair of tones that either ascend or descend in pitch and telling the researcher whether the tones went 'up' or 'down' either verbally, or by pointing to a pictorial response card.

If your children, or those of your friends meet these criteria and you would like to participate please contact Chris Radford for more information.

This study has the approval of the University of Canterbury Human Ethics Committee.

Chris Radford
Mobile: 021-034-0744
cjr120@student.canterbury.ac.nz

Chris Radford
Mobile: 021-034-0744
cjr120@student.canterbury.ac.nz

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cjr120@student.canterbury.ac.nz

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

INFORMATION FOR PARENTS OF PARTICIPANTS IN RESEARCH

PERFORMANCE OF NORMAL-HEARING CHILDREN ON TASKS OF SPEECH AND PITCH PERCEPTION

AIMS OF THE RESEARCH

The main aim of this study is to provide information regarding the performance of children on tests of speech-in-noise and pitch perception.

PARTICIPATION CRITERIA

We are looking normal-hearing children between 6 and 16 years of age. Children should be native English speakers and have no language-related learning disabilities. You are free to withdraw your child from this study at any time without penalty, or any affect on any future audiological care.

DESCRIPTION OF THE PROCEDURE

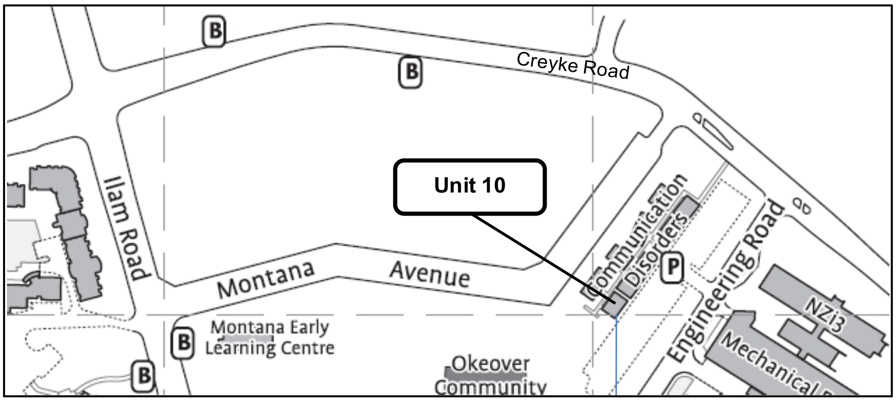
This study involves two appointments lasting approximately one hour each. The first appointment involves measurement of the child's hearing thresholds using standard clinical procedure. Where a hearing loss is indicated, participants will be referred for a full diagnostic hearing assessment in order to determine the true nature of the loss.

Children who pass the hearing screen will then be tested using tests of speech and pitch perception. The speech perception task involves listening to and repeating short sentences in quiet, and in the presence of four-talker babble noise. The pitch perception task involves listening to a pair of tones that either ascend or descend in pitch and telling the researcher whether the tones went 'up' or 'down' either verbally, or by pointing to a pictorial response card.

The second appointment will take place 3 months later and involve a repetition of the speech and pitch perception tests in appointment one in order to test for any learning effects. All appointments will take place at Unit 10 at the Department of Communication Disorders, University of Canterbury located on the corner of Crekye Road, Montana Ave and Engineering Road. Carpark access is via Engineering Road.

BENEFITS AND RISKS

It is not expected that the participants will obtain any direct benefit from the testing sessions. For all of the testing, the stimuli will be presented at everyday, comfortable levels. There is a small risk that the hearing screen



may reveal the presence of a previously undiagnosed hearing loss or middle ear dysfunction. Appropriate referrals for diagnosis and treatment will be made in such cases.

COMPLETION OF THE STUDY

It is estimated that this study will be completed by 1st March 2009. The results of this study will be compared with the results of another study being conducted by the researchers, evaluating the performance of hearing-impaired children using the same tests of speech-in-noise and pitch perception.

It is planned for the research results to be published in appropriate scientific or clinical journals, and the findings may also be presented at international and national conferences or seminars. No information which could lead to your child's identification will be included in any publications or presentations using the data obtained in this study.

ETHICAL APPROVAL

This study has received ethical clearance from the University of Canterbury Human Research Ethics Committee.

If you have any concerns in regards to any aspect of this research, you are encouraged to contact the principal researcher, Chris Radford. Should you have any complaints, you are also able to contact either the Department, the Primary Investigator for the research Valerie Looi.

you have any queries or concerns regarding your personal rights, or the rights of your child as a participant in this study feel free to contact an independent Health and Disability Advocate.

CONTACT DETAILS

THE DEPARTMENT OF COMMUNICATION DISORDERS, UNIVERSITY OF CANTERBURY

PH: +64 (3) 364 2431 (General) FAX: +64 (3) 364 2760 CLINIC PH: +64 (3) 364 2408

Chris Radford, Masters of Audiology Student

PH: +64 (3) 366 7001 ext: 4816 or 4295 EMAIL: cjr120@student.canterbury.ac.nz MOB: +64 21 034 0744

Valerie Looi, Primary Supervisor, Lecturer in Audiology

PH: +64 (3) 366 7001 ext: 3051 EMAIL: valerie.looi@canterbury.ac.nz

Paul Peryman, Associate Supervisor, Senior Audiologist and Clinical Educator

PH: +64 (3) 326 6009 EMAIL: pperyman@vanasch.school.nz

HEALTH AND DISABILITY ADVOCATE SERVICES

PH: 0800 423 638 (Lower North Island) PH: 0800 377 766 (South Island)

FAX: 0800 2787 7678 (Nationwide) EMAIL: advocacy@hdc.org.nz (Nationwide)

THE UNIVERSITY OF CANTERBURY:

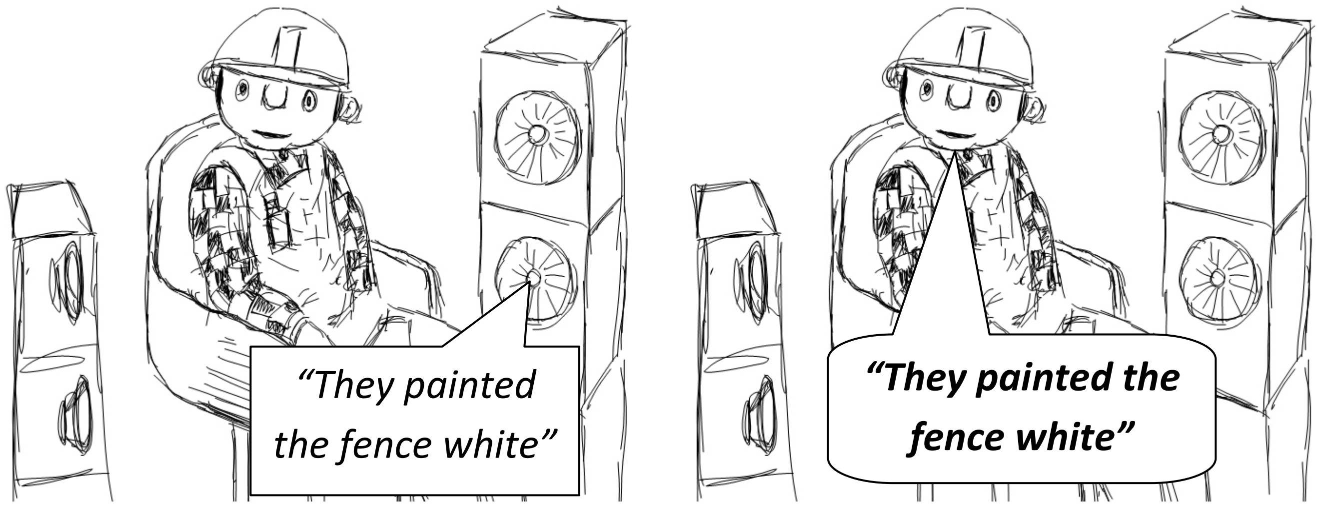
DEPARTMENT OF COMMUNICATION DISORDERS

INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~5-8

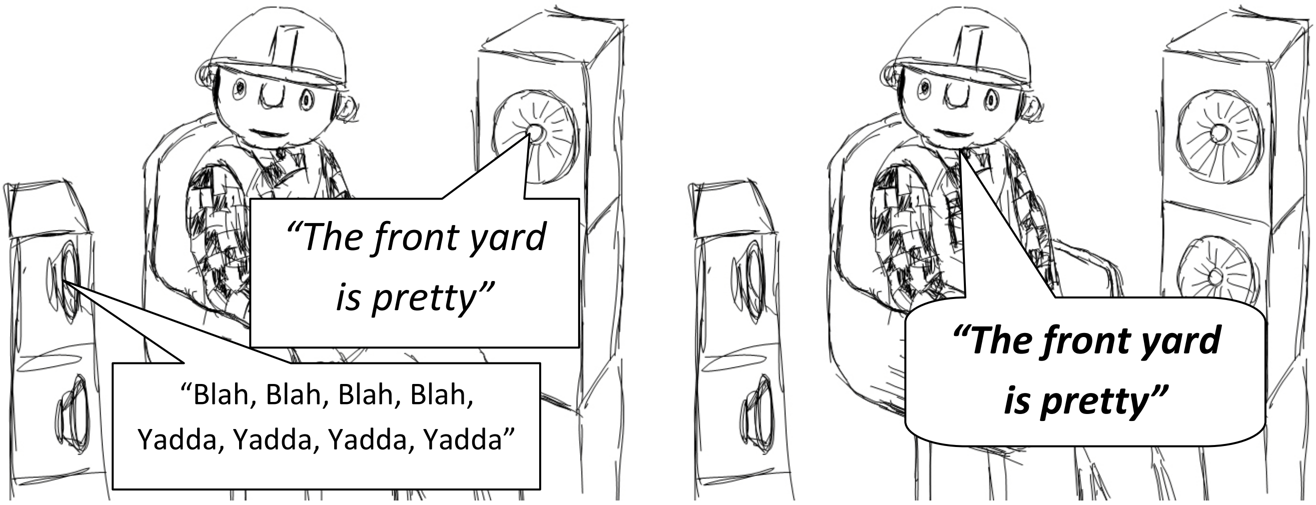
PERFORMANCE OF NORMAL-HEARING CHILDREN ON TESTS OF SPEECH AND PITCH PERCEPTION

We invite you to take part in a listening game challenge as part of work at the University of Canterbury. Four games will be played, and your aim is to get the high score!

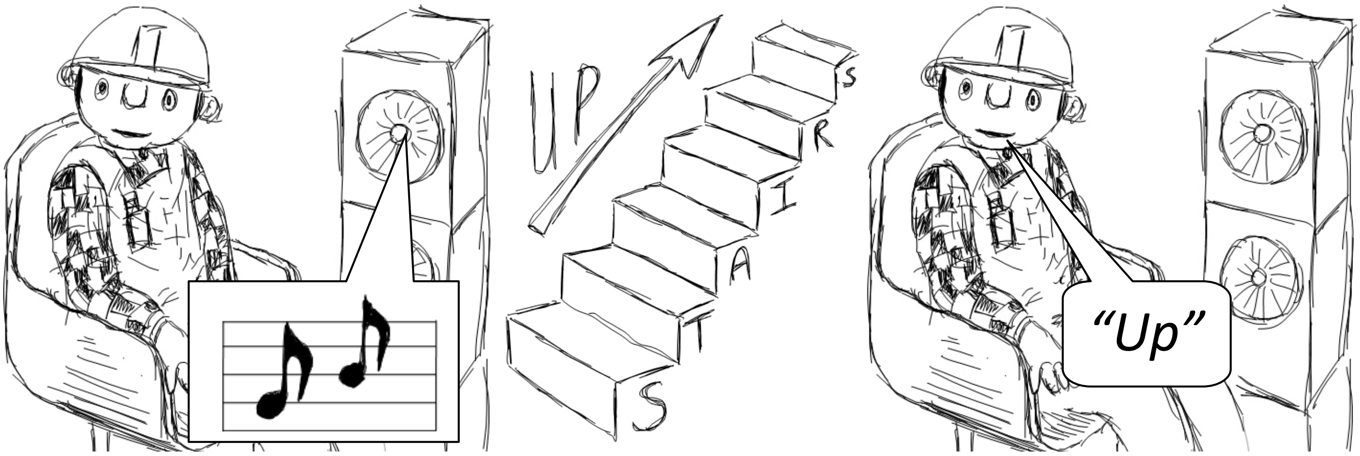
In the first game you'll be given a button and some headphones. Over the headphones you'll hear a series of whistles. Every time you hear a whistle, all you need to do is push the button.



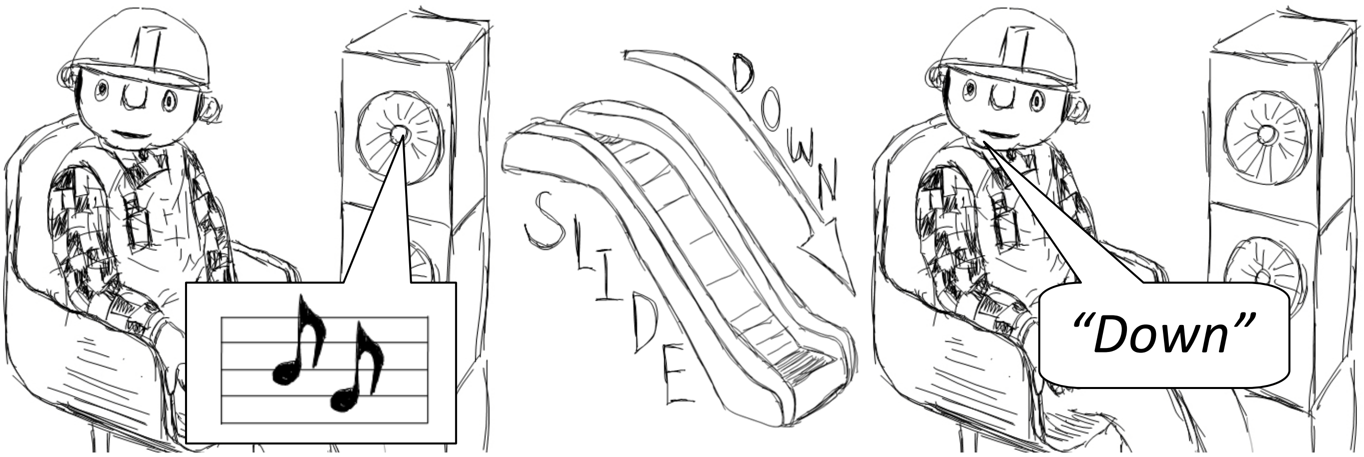
In the second game you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you say "they painted the fence white." If you're not sure or don't know what the woman said, have a guess.



In the third game you'll hear a woman say a sentence over a loudspeaker like in the last game. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling woman and listen to the sentence the other woman is saying. So if she says "the front yard is pretty" you say "the front yard is pretty." If you're not sure or don't know what the woman said, have a guess.



In the fourth game you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes go up in pitch you say "up", or point to the picture of the stairs.



If the two notes go down in pitch you say "down", or point to a picture of a slide. This listening game will be played at three different levels. As you pass each level you'll be able to score more points.

Good luck, we hope to see you soon!

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

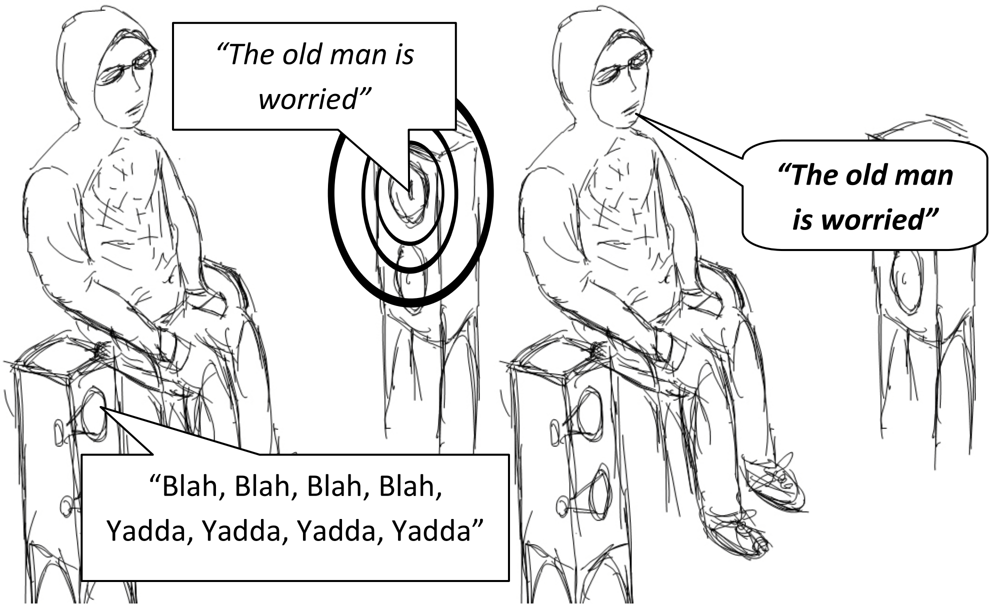
INFORMATION FOR PARTICIPANTS IN RESEARCH AGES ~9-16

PERFORMANCE OF NORMAL-HEARING CHILDREN ON TASKS OF SPEECH AND PITCH PERCEPTION

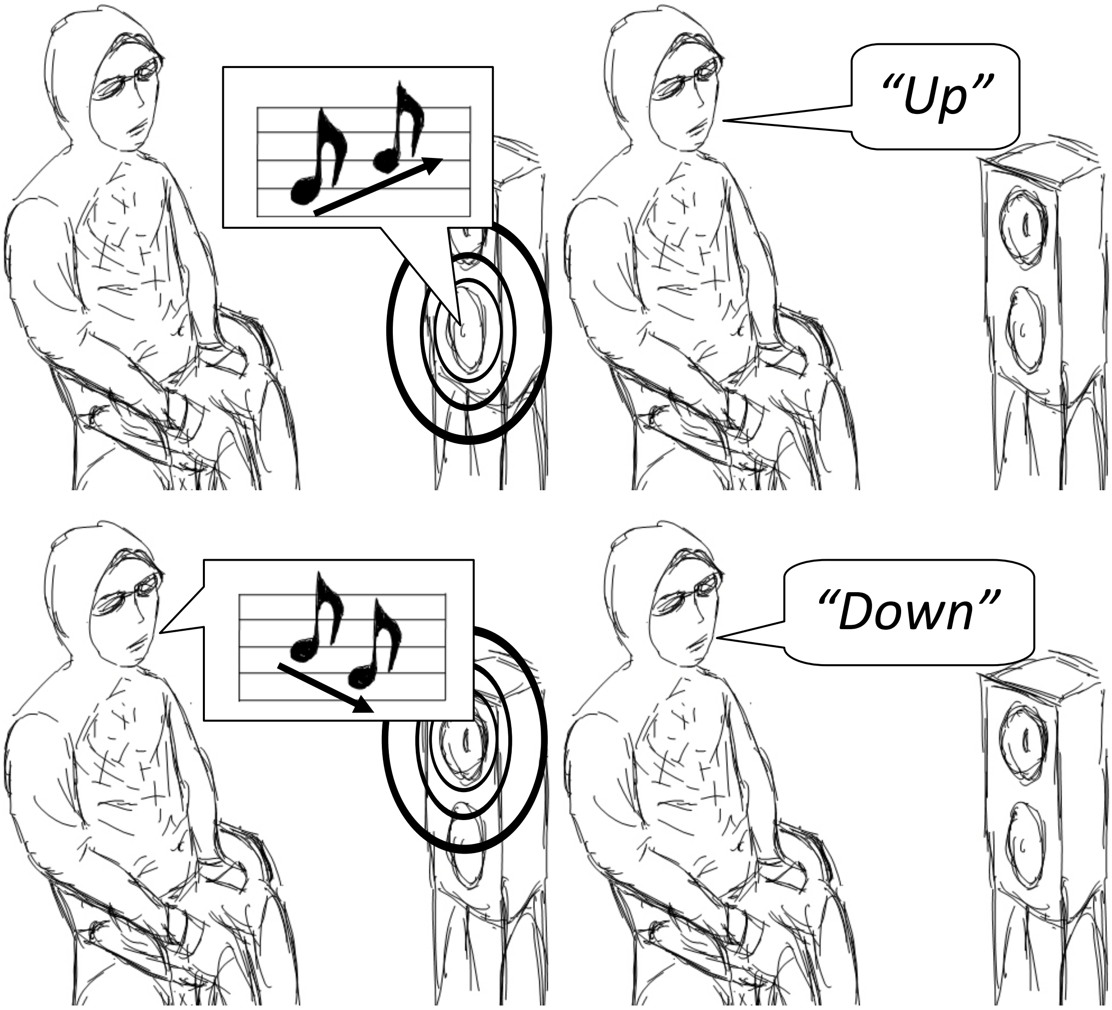
We invite you to take part in a series of listening challenges as part of research at the University of Canterbury. Four challenges are involved, with different levels of difficulty.

In the first challenge you'll be given a button and some headphones. Over the headphones you'll hear a series of beeps. Every time you hear a beep, all you need to do is push the button.

In the second challenge you'll hear a woman say a sentence over a loudspeaker. All you need to do is repeat what the woman says. So if the woman says "they painted the fence white" you'll say "they painted the fence white." If you're not sure or don't know what the man said, have a guess.



In the third challenge you'll hear a woman say a sentence over a loudspeaker as before. At the same time you'll also hear a woman 'babbling' nonsense over another loudspeaker. Your job is to ignore the babbling man and listen to what the other woman is saying. So if she says "the old man is worried" you say "the old man is worried." If you're not sure or don't know what the woman said, have a guess.



In the fourth challenge you'll hear two notes, played one after another. Your job is to tell us whether they're going up or down in pitch. If the two notes rise in pitch you say "up." If the two notes go down in pitch you say "down."

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CHRISTCHURCH NEW ZEALAND

Consent Form for Participants in Research

PROJECT TITLE: PERFORMANCE OF NORMAL-HEARING CHILDREN ON TASKS OF SPEECH AND PITCH PERCEPTION

RESEARCHERS

Christopher Radford	Valerie Looi	Paul Peryman
Masters of Audiology Student	Lecturer in Audiology	Senior Audiologist
PH: (03) 366 7001 ext: 4816	(03) 366 7001 ext: 3051	(03) 326 6009
EMAIL: cjr120@student.canterbury.ac.nz	valerie.looi@canterbury.ac.nz	pperyman@vanasch.school.nz

DECLARATION

I have read and I understand the information sheet for participants taking part in the study designed to investigate the performance of normal-hearing children on tasks of speech and pitch perception dated 6/06/2008. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

I have had the opportunity to use whanau support or a friend to help me ask questions and understand the study.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw my child from the study at any time and this will in no way affect their future health care, continuing health care, academic progress and/ or employment.

I understand that the results of my child's tests are completely confidential, and no material which could identify them will be used in any reports on this study.

I have had the time to consider whether to take part.

I know who to contact if my child has any side effects to any of the procedures, or treatments involved in this study.

I .... (full name) hereby consent for my child

.... (full name) to take part in this study

SIGNATURE .... DATE ....

CONTACT DETAILS OF PARTICIPANT

NAME:..DATE OF BIRTH: ....

PARENT/CAREGIVER(S) NAME(S): ....

ADDRESS:...

....

PHONE:... WORK PHONE: ....

MOBILE:... FAX: ....

EMAIL:...

PREFERRED CONTACT TIME: ....

PREFERRED MODE OF CONTACT: PHONE / WORK PHONE / FAX / MOBILE

Appendix XI: Questionnaire

The Parental Perceptions of Listening Device Performance Questionnaire (PPLDPQ) was adapted to meet the needs of Groups A - D (nBM, CI-only, HA-only and eBM). Copies of each questionnaire follow.

Group A Questionnaire – Appointment 2

NAME PARENT/CAREGIVER: .... DATE: ....

NAME CHILD: ....

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
1. My child wears their cochlear implant every day for at least 80% of their waking hours	☐	☐	☐	☐	☐
2. My child often removes their cochlear implant in noisy situations	☐	☐	☐	☐	☐
3. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
4. I always notice when my child's cochlear implant is not working	☐	☐	☐	☐	☐
5. My child often complains that sounds are too loud	☐	☐	☐	☐	☐
6. My child's cochlear implant is always in good working order	☐	☐	☐	☐	☐
7. My child is unable to recognise the voices of immediate family members	☐	☐	☐	☐	☐
8. My child can recognise songs other children know	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
9. My child enjoys listening to music	☐	☐	☐	☐	☐
10. When I call my child, they are able to recognise my voice without seeing me	☐	☐	☐	☐	☐
11. When answering the telephone, my child is unable to identify familiar voices	☐	☐	☐	☐	☐
12. My child dislikes attending musical performances	☐	☐	☐	☐	☐
13. My child cannot recognise everyday environmental sounds	☐	☐	☐	☐	☐
14. My child does not alert to the sound of the telephone ringing when in another room	☐	☐	☐	☐	☐
15. My child cannot hear the doorbell ring from another room	☐	☐	☐	☐	☐
16. My child responds to their name when called from another room	☐	☐	☐	☐	☐
17. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
18. My child is unable to recognise the sound of nearby birds and point to their location without seeing them first	☐	☐	☐	☐	☐
19. When playing, my child is unable to quickly turn to the location of the voice of a friend who is out of their line of sight	☐	☐	☐	☐	☐
20. My child is able to localise towards the direction of one child's voice	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
21. My child is unable to alert to the sound of an ambulance/fire engine/police car without seeing it first	☐	☐	☐	☐	☐
22. My child can hear the timer beeps of the microwave	☐	☐	☐	☐	☐
Thinking about your child's current situation, please rank the following statements for ***quiet situations***					
23. My child always responds when I call their name	☐	☐	☐	☐	☐
24. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
25. My child has no difficulty understanding conversations taking place on television or radio	☐	☐	☐	☐	☐
26. My child is unable to participate in small group conversations with three or fewer participants	☐	☐	☐	☐	☐
27. I need to constantly repeat myself when talking one on one with my child	☐	☐	☐	☐	☐
28. I can hold a conversation with my child over the telephone without constant repetition	☐	☐	☐	☐	☐
29. My child has no difficulty participating in small group conversations involving three or fewer participants	☐	☐	☐	☐	☐
30. My child has no difficulty listening to someone who is not facing them	☐	☐	☐	☐	☐
31. My child is unable to hold a telephone conversation with an unfamiliar talker	☐	☐	☐	☐	☐

*Thinking about your child's current situation, please rank the following statements for **noisy environments***	STRONGLY DISAGREE	SOMEWHAT DISAGREE	NEITHER AGREE NOR DISAGREE	SOMEWHAT AGREE	STRONGLY AGREE
32. My child can participate in dinner conversation at a restaurant without requiring constant repetition	☐	☐	☐	☐	☐
33. My child is unable to participate in a conversation when travelling in the car	☐	☐	☐	☐	☐
34. My child requires constant repetition when I talk to her during trips to the shopping centre	☐	☐	☐	☐	☐
35. My child can participate in a conversation when the television and radio are on	☐	☐	☐	☐	☐
36. My child never responds to their name in noisy situations	☐	☐	☐	☐	☐
37. My child has is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐
38. My child has no difficulty understanding conversation at the dinner table	☐	☐	☐	☐	☐
39. My child can understand conversations even when several people are talking	☐	☐	☐	☐	☐
40. My child can communicates with others when in a crowd	☐	☐	☐	☐	☐
41. My child is able to actively participate in classroom discussions	☐	☐	☐	☐	☐

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

PLEASE RETURN THE COMPLETED QUESTIONNAIRE TO THE FOLLOWING ADDRESS USING THE INCLUDED PREPAID ENVELOPE

Chris Radford, c/o Department of Communication Disorders

The University of Canterbury, Private Bag 4800, CHRISTCHURCH 8020

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UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

Group B Questionnaire – Appointment 1

NAME PARENT/CAREGIVER: .... DATE: ....

NAME CHILD: ....

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
1. My child wears their cochlear implant every day for at least 80% of their waking hours	☐	☐	☐	☐	☐
2. My child rarely wears their cochlear implant in a classroom setting	☐	☐	☐	☐	☐
3. My child often removes their cochlear implant in noisy situations	☐	☐	☐	☐	☐
4. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
5. I always notice when my child's cochlear implant is not working	☐	☐	☐	☐	☐
6. My child often complains that sounds are too loud	☐	☐	☐	☐	☐
7. My child's cochlear implant is always in good working order	☐	☐	☐	☐	☐
8. My child is unable to recognise the voices of immediate family members	☐	☐	☐	☐	☐
9. My child can recognise songs other children know	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
10. My child enjoys listening to music	☐	☐	☐	☐	☐
11. When I call my child, they are able to recognise my voice without seeing me	☐	☐	☐	☐	☐
12. When answering the telephone, my child is unable to identify familiar voices	☐	☐	☐	☐	☐
13. My child dislikes attending musical performances	☐	☐	☐	☐	☐
14. My child cannot recognise every day environmental sounds	☐	☐	☐	☐	☐
15. My child does not alert to the sound of the telephone ringing when in another room	☐	☐	☐	☐	☐
16. My child cannot hear the doorbell ring from another room	☐	☐	☐	☐	☐
17. My child responds to their name when called from another room	☐	☐	☐	☐	☐
18. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
19. My child is unable to recognise the sound of nearby birds and point to their location without seeing them first	☐	☐	☐	☐	☐
20. When playing, my child is unable to quickly turn to the location of the voice of a friend who is out of their line of sight	☐	☐	☐	☐	☐
21. My child is able to localise towards the direction of one child's voice	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
22. My child is unable to alert to the sound of an ambulance/fire engine/police car without seeing it first	☐	☐	☐	☐	☐
23. My child can hear the timer beeps of the microwave	☐	☐	☐	☐	☐
Thinking about your child's current situation, please rank the following statements for ***quiet situations***					
24. My child always responds when I call their name	☐	☐	☐	☐	☐
25. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
26. My child has no difficulty understanding conversations taking place on television or radio	☐	☐	☐	☐	☐
27. My child is unable to participate in small group conversations with three or fewer participants	☐	☐	☐	☐	☐
28. I need to constantly repeat myself when talking one on one with my child	☐	☐	☐	☐	☐
29. I can hold a conversation with my child over the telephone without constant repetition	☐	☐	☐	☐	☐
30. My child has no difficulty participating in small group conversations involving three or fewer participants	☐	☐	☐	☐	☐
31. My child has no difficulty listening to someone who is not facing them	☐	☐	☐	☐	☐
32. My child is unable to hold a telephone conversation with an unfamiliar talker	☐	☐	☐	☐	☐

*Thinking about your child's current situation, please rank the following statements for **noisy environments***	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
33. My child can participate in dinner conversation at a restaurant without requiring constant repetition	☐	☐	☐	☐	☐
34. My child is unable to participate in a conversation when travelling in the car	☐	☐	☐	☐	☐
35. My child requires constant repetition when I talk to her during trips to the shopping centre	☐	☐	☐	☐	☐
36. My child can participate in a conversation when the television and radio are on	☐	☐	☐	☐	☐
37. My child never responds to their name in noisy situations	☐	☐	☐	☐	☐
38. My child has is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐
39. My child has no difficulty understanding conversation at the dinner table	☐	☐	☐	☐	☐
40. My child can understand conversations even when several people are talking	☐	☐	☐	☐	☐
41. My child can communicates with others when in a crowd	☐	☐	☐	☐	☐
42. My child is able to actively participate in classroom discussions	☐	☐	☐	☐	☐

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Group C Questionnaire – Appointment 1

NAME PARENT/CAREGIVER: .... DATE: ....

NAME CHILD: ....

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
1. My child wears their hearing aids every day for at least 80% of their waking hours	☐	☐	☐	☐	☐
2. My child rarely wears their hearing aids in a classroom setting	☐	☐	☐	☐	☐
3. My child often removes their hearing aids in noisy situations	☐	☐	☐	☐	☐
4. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
5. I always notice when my child's hearing aids are not working	☐	☐	☐	☐	☐
6. My child often complains that sounds are too loud	☐	☐	☐	☐	☐
7. My child's hearing aid is always in good working order	☐	☐	☐	☐	☐
8. My child is unable to recognise the voices of immediate family members	☐	☐	☐	☐	☐
9. My child can recognise songs other children know	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
10. My child enjoys listening to music	☐	☐	☐	☐	☐
11. When I call my child, they are able to recognise my voice without seeing me	☐	☐	☐	☐	☐
12. When answering the telephone, my child is unable to identify familiar voices	☐	☐	☐	☐	☐
13. My child dislikes attending musical performances	☐	☐	☐	☐	☐
14. My child cannot recognise every day environmental sounds	☐	☐	☐	☐	☐
15. My child does not alert to the sound of the telephone ringing when in another room	☐	☐	☐	☐	☐
16. My child cannot hear the doorbell ring from another room	☐	☐	☐	☐	☐
17. My child responds to their name when called from another room	☐	☐	☐	☐	☐
18. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
19. My child is unable to recognise the sound of nearby birds and point to their location without seeing them first	☐	☐	☐	☐	☐
20. When playing, my child is unable to quickly turn to the location of the voice of a friend who is out of their line of sight	☐	☐	☐	☐	☐
21. My child is able to localise towards the direction of one child's voice	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
22. My child is unable to alert to the sound of an ambulance/fire engine/police car without seeing it first	☐	☐	☐	☐	☐
23. My child can hear the timer beeps of the microwave	☐	☐	☐	☐	☐
*Thinking about your child's current situation, please rank the following statements for **quiet situations***					
24. My child always responds when I call their name	☐	☐	☐	☐	☐
25. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
26. My child has no difficulty understanding conversations taking place on television or radio	☐	☐	☐	☐	☐
27. My child is unable to participate in small group conversations with three or fewer participants	☐	☐	☐	☐	☐
28. I need to constantly repeat myself when talking one on one with my child	☐	☐	☐	☐	☐
29. I can hold a conversation with my child over the telephone without constant repetition	☐	☐	☐	☐	☐
30. My child has no difficulty participating in small group conversations involving three or fewer participants	☐	☐	☐	☐	☐
31. My child has no difficulty listening to someone who is not facing them	☐	☐	☐	☐	☐
32. My child is unable to hold a telephone conversation with an unfamiliar talker	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements for ***noisy environments***

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
33. My child can participate in dinner conversation at a restaurant without requiring constant repetition	☐	☐	☐	☐	☐
34. My child is unable to participate in a conversation when travelling in the car	☐	☐	☐	☐	☐
35. My child requires constant repetition when I talk to her during trips to the shopping centre	☐	☐	☐	☐	☐
36. My child can participate in a conversation when the television and radio are on	☐	☐	☐	☐	☐
37. My child never responds to their name in noisy situations	☐	☐	☐	☐	☐
38. My child has is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐
39. My child has no difficulty understanding conversation at the dinner table	☐	☐	☐	☐	☐
40. My child can understand conversations even when several people are talking	☐	☐	☐	☐	☐
41. My child can communicates with others when in a crowd	☐	☐	☐	☐	☐
42. My child is able to actively participate in classroom discussions	☐	☐	☐	☐	☐

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Group D Questionnaire – Appointment 1

NAME PARENT/CAREGIVER: .... DATE: ....

NAME CHILD: ....

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
1. My child wears their hearing aid every day for at least 80% of their waking hours	☐	☐	☐	☐	☐
2. My child rarely wears their hearing aid in a classroom setting	☐	☐	☐	☐	☐
3. My child often removes their hearing aid in noisy situations	☐	☐	☐	☐	☐
4. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
5. I always notice when my child's hearing aid is not working	☐	☐	☐	☐	☐
6. My child often complains that sounds are too loud	☐	☐	☐	☐	☐
7. My child's hearing aid is always in good working order	☐	☐	☐	☐	☐
8. My child is unable to recognise the voices of immediate family members	☐	☐	☐	☐	☐
9. My child can recognise songs other children know	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
10. My child enjoys listening to music	☐	☐	☐	☐	☐
11. When I call my child, they are able to recognise my voice without seeing me	☐	☐	☐	☐	☐
12. When answering the telephone, my child is unable to identify familiar voices	☐	☐	☐	☐	☐
13. My child dislikes attending musical performances	☐	☐	☐	☐	☐
14. My child cannot recognise every day environmental sounds	☐	☐	☐	☐	☐
15. My child does not alert to the sound of the telephone ringing when in another room	☐	☐	☐	☐	☐
16. My child cannot hear the doorbell ring from another room	☐	☐	☐	☐	☐
17. My child responds to their name when called from another room	☐	☐	☐	☐	☐
18. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
19. My child is unable to recognise the sound of nearby birds and point to their location without seeing them first	☐	☐	☐	☐	☐
20. When playing, my child is unable to quickly turn to the location of the voice of a friend who is out of their line of sight	☐	☐	☐	☐	☐
21. My child is able to localise towards the direction of one child's voice	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
22. My child is unable to alert to the sound of an ambulance/fire engine/police car without seeing it first	☐	☐	☐	☐	☐
23. My child can hear the timer beeps of the microwave	☐	☐	☐	☐	☐
Thinking about your child's current situation, please rank the following statements for ***quiet situations***					
24. My child always responds when I call their name	☐	☐	☐	☐	☐
25. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
26. My child has no difficulty understanding conversations taking place on television or radio	☐	☐	☐	☐	☐
27. My child is unable to participate in small group conversations with three or fewer participants	☐	☐	☐	☐	☐
28. I need to constantly repeat myself when talking one on one with my child	☐	☐	☐	☐	☐
29. I can hold a conversation with my child over the telephone without constant repetition	☐	☐	☐	☐	☐
30. My child has no difficulty participating in small group conversations involving three or fewer participants	☐	☐	☐	☐	☐
31. My child has no difficulty listening to someone who is not facing them	☐	☐	☐	☐	☐
32. My child is unable to hold a telephone conversation with an unfamiliar talker	☐	☐	☐	☐	☐

*Thinking about your child's current situation, please rank the following statements for **noisy environments***	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
33. My child can participate in dinner conversation at a restaurant without requiring constant repetition	☐	☐	☐	☐	☐
34. My child is unable to participate in a conversation when travelling in the car	☐	☐	☐	☐	☐
35. My child requires constant repetition when I talk to her during trips to the shopping centre	☐	☐	☐	☐	☐
36. My child can participate in a conversation when the television and radio are on	☐	☐	☐	☐	☐
37. My child never responds to their name in noisy situations	☐	☐	☐	☐	☐
38. My child has is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐
39. My child has no difficulty understanding conversation at the dinner table	☐	☐	☐	☐	☐
40. My child can understand conversations even when several people are talking	☐	☐	☐	☐	☐
41. My child can communicates with others when in a crowd	☐	☐	☐	☐	☐
42. My child is able to actively participate in classroom discussions	☐	☐	☐	☐	☐

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

THE UNIVERSITY OF CANTERBURY:

DEPARTMENT OF COMMUNICATION DISORDERS

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Group A Questionnaire – Appointment 4

NAME PARENT/CAREGIVER: .... DATE: ....

NAME CHILD: ....

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
1. My child wears their hearing aid every day for at least 80% of their waking hours	☐	☐	☐	☐	☐
2. My child rarely wears their hearing aid in a classroom setting	☐	☐	☐	☐	☐
3. My child often removes their hearing aid in noisy situations	☐	☐	☐	☐	☐
4. My child is often bothered by impact noises such as the clatter of plates, or clapping of hands	☐	☐	☐	☐	☐
5. I always notice when my child's hearing aid is not working	☐	☐	☐	☐	☐
6. My child often complains that sounds are too loud	☐	☐	☐	☐	☐
7. My child's hearing aid is always in good working order	☐	☐	☐	☐	☐
8. My child is unable to recognise the voices of immediate family members	☐	☐	☐	☐	☐
9. My child can recognise songs other children know	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
10. My child enjoys listening to music	☐	☐	☐	☐	☐
11. When I call my child, they are able to recognise my voice without seeing me	☐	☐	☐	☐	☐
12. When answering the telephone, my child is unable to identify familiar voices	☐	☐	☐	☐	☐
13. My child dislikes attending musical performances	☐	☐	☐	☐	☐
14. My child cannot recognise every day environmental sounds	☐	☐	☐	☐	☐
15. My child does not alert to the sound of the telephone ringing when in another room	☐	☐	☐	☐	☐
16. My child cannot hear the doorbell ring from another room	☐	☐	☐	☐	☐
17. My child responds to their name when called from another room	☐	☐	☐	☐	☐
18. My child always turns directly towards me when I call them from across a room	☐	☐	☐	☐	☐
19. My child is unable to recognise the sound of nearby birds and point to their location without seeing them first	☐	☐	☐	☐	☐
20. When playing, my child is unable to quickly turn to the location of the voice of a friend who is out of their line of sight	☐	☐	☐	☐	☐
21. My child is able to localise towards the direction of one child's voice	☐	☐	☐	☐	☐

Thinking about your child's current situation, please rank the following statements	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
22. My child is unable to alert to the sound of an ambulance/fire engine/police car without seeing it first	☐	☐	☐	☐	☐
23. My child can hear the timer beeps of the microwave	☐	☐	☐	☐	☐
*Thinking about your child's current situation, please rank the following statements for **quiet situations***					
24. My child always responds when I call their name	☐	☐	☐	☐	☐
25. My child can participate in a conversation with family members without repetition	☐	☐	☐	☐	☐
26. My child has no difficulty understanding conversations taking place on television or radio	☐	☐	☐	☐	☐
27. My child is unable to participate in small group conversations with three or fewer participants	☐	☐	☐	☐	☐
28. I need to constantly repeat myself when talking one on one with my child	☐	☐	☐	☐	☐
29. I can hold a conversation with my child over the telephone without constant repetition	☐	☐	☐	☐	☐
30. My child has no difficulty participating in small group conversations involving three or fewer participants	☐	☐	☐	☐	☐
31. My child has no difficulty listening to someone who is not facing them	☐	☐	☐	☐	☐
32. My child is unable to hold a telephone conversation with an unfamiliar talker	☐	☐	☐	☐	☐

*Thinking about your child's current situation, please rank the following statements for **noisy environments***

	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
33. My child can participate in dinner conversation at a restaurant without requiring constant repetition	☐	☐	☐	☐	☐
34. My child is unable to participate in a conversation when travelling in the car	☐	☐	☐	☐	☐
35. My child requires constant repetition when I talk to her during trips to the shopping centre	☐	☐	☐	☐	☐
36. My child can participate in a conversation when the television and radio are on	☐	☐	☐	☐	☐
37. My child never responds to their name in noisy situations	☐	☐	☐	☐	☐
38. My child has is unable to participant in a conversation on a bus or train	☐	☐	☐	☐	☐
39. My child has no difficulty understanding conversation at the dinner table	☐	☐	☐	☐	☐
40. My child can understand conversations even when several people are talking	☐	☐	☐	☐	☐
41. My child can communicates with others when in a crowd	☐	☐	☐	☐	☐
42. My child is able to actively participate in classroom discussions	☐	☐	☐	☐	☐

Thank you for completing this questionnaire